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Life Cycle Assessment of Electricity from Wave Power

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Abstract

The use of ocean wave energy for electricity production has considerable potential, though it has proven to be difficult. A technology utilizing the heaving (up-and-down) motions of the waves was conceived at Uppsala University in the early 2000's, and is being further developed for commercial use by Seabased Industry AB.

The purpose of this master's degree project was to increase the knowledge of the environmental performance of Seabased's wave energy conversion concept and identifying possible areas of improvement. This was done by conducting a life cycle assessment (LCA) of a hypothetical prototype wave power plant. All flows of materials, energy, emissions and waste were calculated for all stages of a wave power plant's life cycle. The potential environmental impact of these flows was then assessed, using the following impact categories:

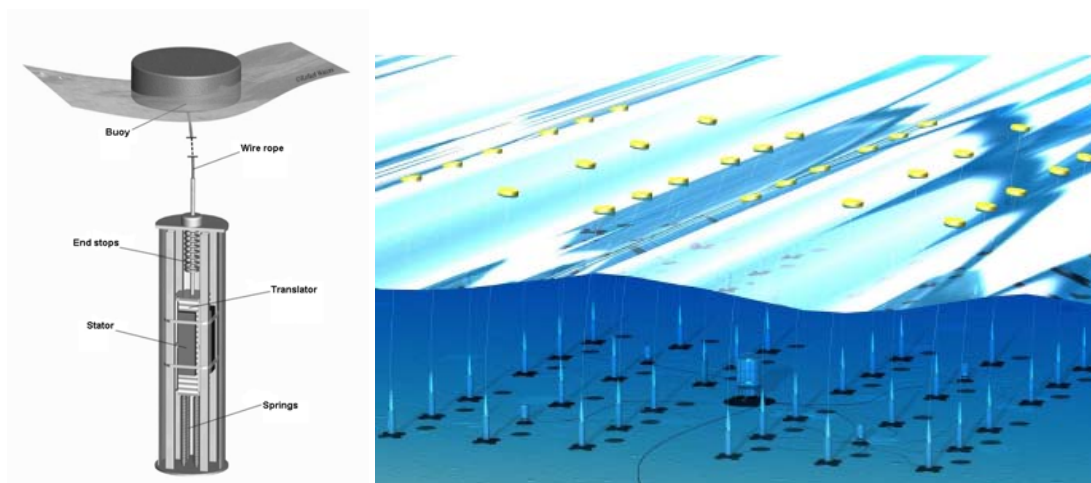
- Emission of greenhouse gases
- Emission of ozone depleting gases
- Emission of acidifying gases
- Emission of gases that contribute to the forming of ground-level ozone
- Emission of substances to water contributing to oxygen depletion (eutrophication)
- Energy use (renewable and non-renewable)
- Water use

The methodology used was that prescribed by the ISO standard for Environmental Product Declarations (EPD) and further defined by the International EPD Programme. The potential environmental impact was calculated per kWh of wave power electricity delivered to the grid.

The main result of the study is that the potential environmental impact of a wave power plant mainly stems from the manufacturing phase. In particular, the production of steel parts makes a large contribution to the overall results. Future wave power plant designs are expected to be considerably more material efficient, meaning that there are large possibilities to improve the environmental performance of this technology.

SAMMANFATTNING

Havsvågor innehåller enorma mängder förnybar energi. Många försök har gjorts att utnyttja denna energi, men det har visat sig vara svårt. Ett nytt koncept för att omvandla vågornas vertikala rörelser till elektricitet utvecklades under början av 2000-talet vid Uppsala universitet och utvecklas nu vidare för marknaden av Uppsalaföretaget Seabased Industry AB. Denna teknik bygger på linjära generatorer (d.v.s. generatorer vars rörliga del inte roterar utan rör sig upp och ner) placerade på fundament på havsbotten. Generatorns rörliga del, translatoren, sitter fast med ett vajerrep i en boj som rör sig upp och ner med havsytan. Translatoren är klädd med permanentmagneter och rör sig upp och ner inuti generatorns fasta del, statorn, som i princip är en stor spole. På så sätt alstras elektricitet. Ett stort antal sådana generatorer bildar en vågkraftpark.



T.V: BOJ OCH LINJÄRGENERATOR. GENERATORN PLACERAS PÅ HAVSBOTTEN OCH DESS RÖRLIGA DEL, TRANSLATORN, RÖR SIG UPP OCH NER MED BOJEN SOM FLYTER PÅ HAVSYTAN. T.H: EN VÅGKRAFTPARK SOM DEN SKULLE KUNNA SE UT I FRAMTIDEN.

Syftet med detta examensarbete var att öka kunskapen om den miljöpåverkan som orsakas av denna vågkraftsteknik, genom att genomföra en livscykelanalys av en vågkraftpark. Livscykelanalys (LCA) är en kvantitativ metod för att bedöma produkters och tjänsters miljöpåverkan. Förbrukning av resurser och utsläpp av föroreningar beräknas för alla delar av produktens livscykel, från utvinning av råmaterial tills produkten använts färdigt. Miljöpåverkan delas in i olika kategorier och utsläpp av olika föroreningar summeras med hjälp av så kallade karakteriseringsfaktorer. Exempelvis beräknas utsläppen av växthusgaser i koldioxidekvivalenter. Metan beräknas bidra till global uppvärmning 23 gånger så mycket som koldioxid. När man summerar ihop utsläpp av växthusgaser multipliceras därför utsläppen av metan med karakteriseringsfaktorn 23, medan koldioxidutsläpp multipliceras med 1.

Resultaten av en livscykelanalys beror till stor del på vilken metod och vilka systemgränser som används. Därför finns standarder för hur LCA ska genomföras. Miljövarudeklarationer är en typ av miljömärkning som baseras på livscykelanalyser genomförda i enlighet med ISO-standarderna för LCA. Syftet med miljövarudeklarationer är att förenkla jämförelser av

miljöprestanda mellan olika produkter som fyller samma funktion. Denna livscykelanalys genomfördes enligt riktlinjerna för miljövarudeklarationer. Miljöpåverkan beräknades per kWh el levererad till elnätet och följande miljöpåverkanskategorier användes:

- Utsläpp av växthusgaser
- Utsläpp av ozonförstörande gaser
- Utsläpp av försurande ämnen
- Utsläpp av ämnen som bidrar till övergödning
- Utsläpp av ämnen som bidrar till bildandet av marknära ozon
- Energiförbrukning
- Vattenförbrukning

Analysen gjordes för två fall. Det första var en vågkraftpark bestående av 1000 generatorer, placerad utanför den svenska västkusten, där vågorna är ganska små. I det andra scenariot placeras en likadan park utanför norska kusten. Vågorna är större utanför Norge och man får alltså ut mer elektricitet. Eftersom vågkraftverken tillverkas i Lysekil blir dock transporterna till utlägningsplatsen betydligt längre i det norska fallet.

Resultaten av analysen visar att konstruktionsfasen orsakar största delen av den miljöpåverkan som orsakas av en vågkraftpark. Det är framför allt tillverkningen av stål till vågkraftverken som förbrukar resurser och orsakar utsläpp. Med andra ord är materialeffektivitet det absolut viktigaste att fokusera på för att minska vågkraftens miljöpåverkan. De vågkraftverk som analyseras i denna studie kan sägas vara prototyper och åtgången av stål beräknas bli betydligt – kanske så mycket som femtio procent - mindre i framtida konstruktioner. Med andra ord finns det stor potential att minska systemets miljöpåverkan. I studien antogs generatorfundamenten bestå av armerad betong, som då utgjorde över åttio procent av vågkraftparkens totala vikt. Betongtillverkning visade sig dock stå för en relativt liten del (som mest tio procent) av miljöpåverkan. Permanentmagneterna, en legering av neodymium, järn och bor, beräknades bidra till lika stor andel av miljöpåverkan, trots att de utgör mindre än en procent av den totala vikten.

Transporter av vågkraftverk till sjöss bidrar till en ganska liten del av miljöpåverkan. Detta innebär att en vågkraftpark utanför Norges kust får mycket bättre miljöprestanda än en park strax utanför Lysekil, trots att transportavståndet är betydligt kortare i det senare fallet. I studien beräknades även vågkraftparkens energiåterbetalningstid, det vill säga den tid det tar för parken att generera den mängd energi som används för att tillverka, underhålla och kassera den. I det norska fallet blev energiåterbetalningstiden cirka tre år, medan den blev nästan tio år i det svenska fallet. Med tanke på att parkens livslängd antas vara tjugo år är detta ett mycket dåligt resultat.

Osäkerheten i resultaten beror dels på osäkerheter i bakgrundsdata (exakt hur mycket svaveldioxid orsakar egentligen produktionen av ett kilo stål?). Osäkerheter i bakgrundsdata uppskattades med hjälp av Monte Carlo-simulering. Denna osäkerhet visade sig vara störst (cirka 50 %) gällande utsläpp av ozonförstörande gaser och minst (cirka 5 %) gällande utsläpp av växthusgaser. Eftersom studien avser hypotetiska vågkraftparker har många antaganden och uppskattningar gjorts, vilket också orsakar osäkerhet i resultaten. Även om man tar hänsyn till denna osäkerhet bör dock de slutsatser som redovisas ovan kunna dras.

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1 INTRODUCTION

1.1 BACKGROUND

1.1.1 WAVE ENERGY CONVERSION – THE UPPSALA CONCEPT

The oceans of the world represent an enormous, renewable source of energy which so far remains virtually unexploited. A growing energy demand combined with pressing environmental concerns makes wave power interesting from an economical as well as an environmental point of view. However, wave energy conversion has proven to be difficult. In spite of decades of research and thousands of patents there is still no consensus on the best way to harness the energy of ocean waves. Waves are an irregular source of energy and the variations in power flow can be very large – when a storm hits, the power flow of the waves can be fifty times larger than the average (1). Further, the corrosive environment and difficulties with accessibility for maintenance out at sea present problems that must be solved. Designing a device that is economically viable as well as robust enough to handle the rough conditions of the ocean is truly a challenge.

The wave energy conversion research project at Uppsala University is based on a system utilizing the heaving (up-and-down) movement of the waves. A buoy floating on the ocean surface is connected by a wire rope to a linear generator on the ocean floor. The generator consists of a moving part (translator), which is clad with permanent magnets, and a stationary part (stator) with three-phase cable windings. The translator moves up and down, following the motions of the buoy, generating a voltage in the cable windings of the stator. The principle is the same as when a magnet is moved back and forth through a coil, with the translator representing the magnet and the stator representing the coil. A wave power plant is envisioned to consist of a large number (up to several thousands) of generators placed in arrays on the seafloor. Figure 1 is a schematic illustration of a wave energy converter and figure 2 shows a vision of what a wave power plant of this type might look like in the future.

The benefits of this concept are that the electrical components of the plant are placed on the bottom of the sea, sheltered from the large forces acting on the sea surface. Using linear generators also means that no hydraulic or mechanic system is needed to convert the wave motions into the fast, rotating movement of a conventional generator. This means a less complex and more robust construction. Another benefit is the use of many small units instead of one large construction. This decreases the vulnerability of the plant – a few generators can break without significantly affecting the total electricity production of the plant. The technology is further described in chapter 4.

The described wave energy conversion system is currently being further developed for commercial use by Seabased Industry AB in Uppsala. The technology is at an early stage of development and the wave energy converters so far constructed by the company are more or less prototypes. The hope is that wave power in the future will be both economically viable and environmentally sound.

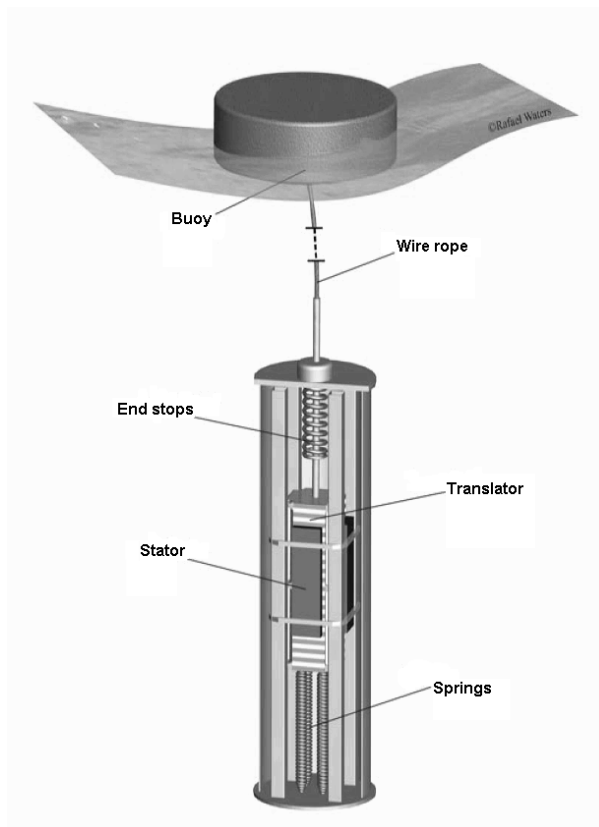


FIGURE 1: THE STRUCTURE OF A WAVE ENERGY CONVERTER (WEC). THE TYPE OF WEC USED IN THE PRESENT STUDY DIFFERS FROM THIS SCHEMATIC BY NOT USING SPRINGS TO PULL THE PISTON DOWN. INSTEAD, THE TRANSLATOR WILL MOVE DOWNWARDS IN THE WAVE TROUGHS BY ITS OWN WEIGHT. ©RAFAEL WATERS

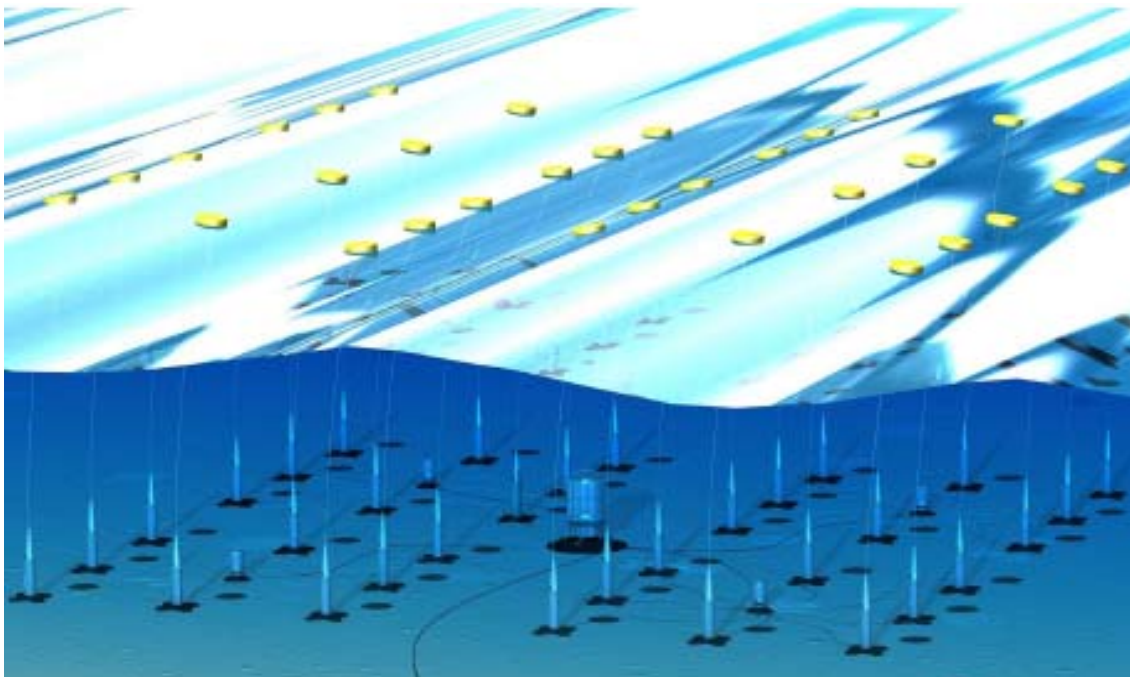


FIGURE 2: AN ILLUSTRATION OF WHAT A WAVE POWER PLANT MIGHT LOOK LIKE IN THE FUTURE. © SEABASED INDUSTRY AB

1.1.2 LIFE CYCLE ASSESSMENT

Early attempts to reduce the strain caused by human activities on the environment consisted mainly of reducing point emissions of pollutants from industries, sewage plants and other facilities. The effectiveness of this approach proved to be limited. As environmental problems began to assume a global rather than local scale the need of a holistic perspective became evident. When developing an "environmentally friendly" product or service the whole life cycle must be studied. Life Cycle Assessment (LCA) is a method for quantitatively assessing the environmental impact caused by a product, an industrial process or a service throughout its entire life cycle – "from the cradle to the grave". For all stages of the life cycle, input of raw materials and energy is calculated as well as output of emissions and waste. The environmental impacts of these flows are then assessed. The goal may be to compare two products performing the same function, to decide between alternative production processes or develop an efficient system for recycling of packaging materials.

The first life cycle assessments were made as early as the late 1960s, but the use of LCA developed relatively slowly until the beginning of the 90s. In the late 80s the Society for Environmental Toxicology and Chemistry (SETAC) developed a framework for development and harmonization of the LCA methodology. One important application was the attempt to reduce the amount of waste deposition. In Sweden LCA-studies concerning different kinds of packaging materials provided a basis for legislation about producer responsibility. The use of LCA increased during the 90s and was applied by governments as well as corporations as basis for policies, product development and marketing. During this period the International Organization for Standardization (ISO) began developing a standardized description of the LCA methodology (2). Since 2006 the two ISO standards concerning LCA are ISO 14040 (Principles and framework) and ISO 14044 (Requirements and guidelines). Standardisation of LCA methodology and the compilation of LCI databases is making LCA an increasingly practicable tool for many different purposes. An increasingly important application of LCA is environmental product declarations, described further below.

1.1.3 ENVIRONMENTAL PRODUCT DECLARATIONS

In order to facilitate environmental comparisons between products and thereby promote environmental improvement, an ISO standardization of what is called Type III environmental labelling was developed (3). Type III labels are environmental product declarations (EPD) containing quantified environmental information based on life cycle assessment performed according to the ISO standards 14040 and 14044. An EPD also provides additional environmental information such as impact on biodiversity and risk assessment on human health and environment. The ISO standard for EPDs is ISO 14025.

The implementation of ISO 14025 can differ, making comparison between EPDs problematic. To deal with this problem the EPD®system was developed in the late 1990s. In early 2008 a revised version of the system, the International EPD®system was launched. The system was initiated by industry and is managed by the International EPD Consortium

(IEC), a non-profit global network of interested parties. The Swedish Environmental Management Council (Miljöstyrningsrådet) has played an important part in the development of the EPD®system. The main objective of the system is to

[...] help and support organisations to communicate the environmental performance of their products (goods and services) in a credible and understandable way by

- offering a complete programme for any interested organisation to develop and communicate EPDs according to ISO 14025, and
- to support other EPD programmes (i.e. national, sectorial etc.) in seeking cooperation and harmonisation and helping organisations to broaden the use of their EPDs on an international market. (4)

The EPD®system regulates the implementation of the ISO standards for LCA and EPD through the General Programme Instructions (4). The instructions are supplemented by calculation rules specific for different product groups. These Product Category Rules (PCR) are developed by institutions involving LCA experts, companies and branch organizations in cooperation. To ensure the credibility and market acceptance of the EPD®system all EPDs developed within the system must be verified by an independent and accredited verifier. The EPD can then be registered and the EPD® logotype can be used.

1.2 PURPOSE

The electricity produced in a wave power plant does not stem from fossil fuels. However, this does not automatically mean that wave power is an "environmentally friendly" method for electricity production. The purpose of this master's degree project is to conduct a life cycle assessment of electricity produced using Seabased's wave power concept. The study aims at identifying parts of the life cycle causing large environmental impacts, thus representing possible areas of improvement.

The LCA will be performed according to the LCA methodology rules prescribed in the PCR for electricity production, developed within the International EPD® system (5). The results of the study will not be comparable to LCA results for other modes of electricity production based on mature technologies. However, as the technology develops from the prototype stage into commercially viable systems, the present work may be further developed, producing comparable results.

1.3 OUTLINE

Chapter 2 presents LCA methodology and important concepts. In chapter 3 the goal and scope of the present LCA study are defined. The studied system is described in chapter 4 and chapter 5 presents the methodology used for the study. The results of the study are presented in chapter 6 and further interpreted in chapter 7. In chapter 8, overall conclusions of the study are presented as well as an outlook on possible future work.

2 LCA CONCEPTS AND METHODOLOGY

Basically, conducting an LCA means gathering data about input and output flows of resources and emissions to and from a system, and then making a quantitative statement about the potential environmental impact of these flows. However, there are many ways to go about this and the results of the LCA will differ widely depending on the methodology used. This chapter gives a brief walk-through of LCA methodology and important concepts, mainly based on (2), (6), (7) and (8).

The ISO standard divides the LCA procedure into four phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact Assessment
4. Interpretation

It is often emphasized that LCA is an iterative process and that the four phases cannot be seen as four steps to be performed one after another. The four phases are further described below.

2.1 GOAL AND SCOPE DEFINITION

Defining the goal and scope of an LCA study is very important, since it sets the conditions under which the study is performed. The goal of the study may be to compare the environmental performance of different products, to guide the design process of a new product or to find ways to reduce the environmental burden of a product or service. The LCA results may be used internally, e.g. as basis for "eco-design" or externally, for marketing or eco-labelling. The scope of the LCA project is then decided by the intended application of the study.

The scope is defined in terms of

- **functional unit** and **reference flow**
- geographical, technological and temporal coverage
- **system boundaries** and **allocation** methods
- choice of **elementary flows** and **environmental impact categories** to include in the study
- **cut-off rules**, data quality requirements, overall level of detail of the study

The **functional unit** of an LCA is the reference unit for the study, basically a clearly defined "amount" of the function performed by the studied system. For example, the environmental

impacts of fuel production is often calculated per MJ of fuel energy content. The **reference flow** is the “amount” of the product system needed to produce the functional unit. The reference flow may be for instance the production of 0,02 liters of diesel, corresponding to 1 MJ fuel energy.

By geographical, technological and temporal coverage is meant a definition of which geographical region, technology and time period is reflected by the LCA. The data might for example reflect Swedish best available technology in the 1990s or the technology used at a specific production site in the year 2005.

System boundaries define processes included in the studied system. The choice of system boundaries will have great impact on the results of the LCA. The ideal system boundaries for a product system would be infinite, meaning that all processes associated to the system would be assessed in an infinite spatial and temporal perspective. Naturally, this is not possible and the system boundaries should be set so that all processes relevant in relation to the goal of the study are included.

Allocation of environmental burdens to different functions of a product system is an important part of the LCA methodology. For example a production process may result in more than one product and it must be determined which product(s) should bear which environmental burdens of the process. Combined heat and power (CHP) plants are typical examples, where the environmental burdens of the plant must be attributed to the heat and/or electricity production. Common allocation methods are

- allocation according to physical causal relationships, e.g. by mass
- allocation according to economical factors, e.g. by market value

The problem of multi-output processes can also be handled through system expansion. This means that the studied system is expanded to include all output products of the process. The functional unit could for instance be changed from “1 kWh of electricity produced in a CHP plant” to “1kWh of electricity and 2 kWh of heat produced in a CHP plant”. This eliminates the need to allocate the ISO standards for LCA

Elementary flows are flows of resources, emissions and waste across the system boundary. In an LCA these flows are categorized into **environmental impact categories**, using characterization factors. For instance, the environmental impact category of global warming potential is expressed in carbon dioxide equivalents and all substances contributing to this impact category are multiplied by a characterization factor reflecting the relative global warming potential of the substance.

Cut-off rules prescribe a limit for excluding processes or flows that are of negligible importance to the study. A commonly used cut-off rule is the “1 percent-rule”, stating that 99 percent of the mass flow, energy content and environmental impact of the product system shall be included in the study. In principle the only way to determine whether this criterion is fulfilled is of course to inventory all flows. In reality the cut-off rule is applied using estimations and expert judgement.

2.2 INVENTORY ANALYSIS

The inventory analysis phase consists of identifying all processes included in the product system, collecting data for these processes, carrying out allocation and calculating the resulting flows of input and output. The main result of the inventory analysis is an inventory table listing the quantified elementary flows to and from the system. The scope definition phase and the inventory analysis phase are closely connected. The scope definition guides the data collection and calculations, but the relationship works both ways. For instance, the need for adjustment of e.g. system boundaries or allocation methods often appears during the inventory analysis phase. These first two phases of an LCA are often referred to as Life Cycle Inventory, LCI.

2.3 IMPACT ASSESSMENT

In this phase the final results of the LCA are obtained. The inventoried elementary flows are categorized into environmental impact categories, e.g. global warming potential, ozone depletion potential or non-renewable energy use. One substance can contribute to several impact categories. For instance, the release of nitrogen oxides can contribute to acidification as well as eutrophication.

Several methods have been developed to aggregate the potential environmental impact of a product system into a single impact category. The purpose of this is to obtain a single parameter for comparisons between product systems. In order to do this the result for each environmental impact category is weighted according to relative importance. Because of the obvious problems associated with objectively deciding which are the most important environmental impacts, weighting is rarely used in LCA today. Instead the LCA results are presented as potential environmental impacts by the different categories. Weighting is not used when preparing an EPD.

2.4 INTERPRETATION

In the interpretation phase the results of the analysis, assumptions and choices made are evaluated and conclusions are drawn. The interpretation phase can consist of:

- consistency check
- completeness check
- contribution analysis
- sensitivity and uncertainty analysis

The purpose of a consistency check is to evaluate whether the assumptions, methods and data used in the analysis are consistent with the goal and scope of the LCA. In the completeness check it is determined whether all relevant processes and data are included in the study. The completeness check can for instance be performed by a technical expert.

Based on the results of these surveys the need for methodological changes or collection of more detailed data may be identified. In other words the LCA work must be evaluated continuously throughout the entire process.

2.5 LIMITATIONS OF LCA

An LCA does not give a complete picture of the environmental performance of a product or a service. First of all, an LCA does not take into account all environmental aspects of a product system. In particular, local effects on e.g. eco systems are not reflected in the results of an LCA. Also, the temporal or geographical context of emissions and resource use is generally not considered. For instance, the actual impacts caused by emissions of acidifying substances depend to a large extent on the characteristics of the recipient. The time span over which a pollutant is emitted may also be of importance, since the environment may be able to handle small emissions over a long period of time whereas a large single emission may cause considerably more damage.

When comparing products or services the choice of environmental impact categories will be very important for the results. When, for instance, comparing nuclear power to other power production methods, the aspect of radioactive waste should probably be included to produce a "fair" result. Then there is also the problem of deciding which environmental impact is the most important.

The results of an LCA depend very much on system boundaries and other methodological aspects. This means that two LCAs for the same product may show very different results. This is a problem that has received considerable attention. Through standardization and database development the aim is to make LCA a reliable tool for e.g. product development and policy choices.

3 GOAL AND SCOPE

3.1 GOAL

The overall purpose of this LCA is to increase the knowledge of the environmental performance of the wave energy conversion system developed by Seabased Industry AB. The main intended application of the study is

- support for product development (choice of materials, production methods, etc.)
- to provide a basis for future environmental product declaration
- commercial and public information

The LCA is performed according to the LCA methodology rules of the International EPD® system. The governing documents are the **Product Category Rules for preparing an EPD for electricity production** (5) and the **EPD General Programme Instructions** (4) with **supporting annexes** (9), (10), henceforth referred to as the PCR, GPI and GPI Annexes respectively. Deviations from the PCR are mostly due to the fact that the studied system does not yet exist, and are described in chapter 3.2 below.

3.2 SCOPE

3.2.1 FUNCTIONAL UNIT AND REFERENCE FLOW

The functional unit used in this LCA is **1 kWh net of electricity from wave power produced and delivered to the grid**. By “1 kWh net” is meant that electricity used for operation of the system is subtracted from the total amount of electricity produced. The reference flow is the construction, operation and end-of-life phase of the corresponding fraction of a wave power plant with a rated power of 20 MW, as described in chapter 4.

3.2.2 GEOGRAPHICAL, TEMPORAL AND TECHNOLOGICAL COVERAGE

The LCA will reflect a wave power plant constructed in the near future. The plant is assumed to be placed off the coast of Sweden or Norway and the production of the plant is assumed to take place in Lysekil. Thus the LCA reflects Scandinavian/Swedish conditions. Data regarding production of raw materials, semi-finished products and components reflect the geographical region where the processes are assumed to take place.

About temporal coverage the PCR states that for the operational phase “data shall reflect one reference year or an annual average of a defined reference period”. Since the studied system does not yet exist, data concerning electricity consumption, maintenance, availability and annual production of the plant is based on calculations and estimations.

The PCR also states that data shall reflect the technology actually used, which in this case translates into technology that is planned to be used. The estimated technical life of the wave power plant is twenty years. During this period technologies used in e.g. maintenance, dismantling and waste treatment are expected to differ from those used today. However, speculations about future technology development would present very large uncertainties. Thus the system studied is a wave power plant constructed, operated and dismantled using present technology.

3.2.3 SYSTEM BOUNDARIES

The LCA includes the full life cycle of a wave power plant, consisting of 1000 generators and point absorbers (buoys), marine substations and sea cable, from the extraction of raw materials to the disposal of waste. The life cycle is divided into upstream processes, operational phase and downstream processes.

Upstream processes include

- extraction and transportation of raw materials
- production and transportation of semi-finished products (e.g. steel profiles)
- manufacturing and transportation of components
- manufacturing of and reinvestment in wave energy converters and sea cables
- deployment of the plant
- transportation and treatment (deposit/destruction) of waste generated in upstream processes

Operational phase includes

- operation and maintenance of the plant
- transmission of electricity to grid

Downstream processes include

- dismantling of wave energy converters, transportation and deposit/destruction of waste

Processes excluded from the life cycle are:

- manufacturing of marine substations (switchgear, transformers)
- construction, reinvestment and dismantling of buildings and machines (capital goods) used in the included processes
- accidents and breakdowns

System boundaries are shown in a simplified process tree in figure 3.

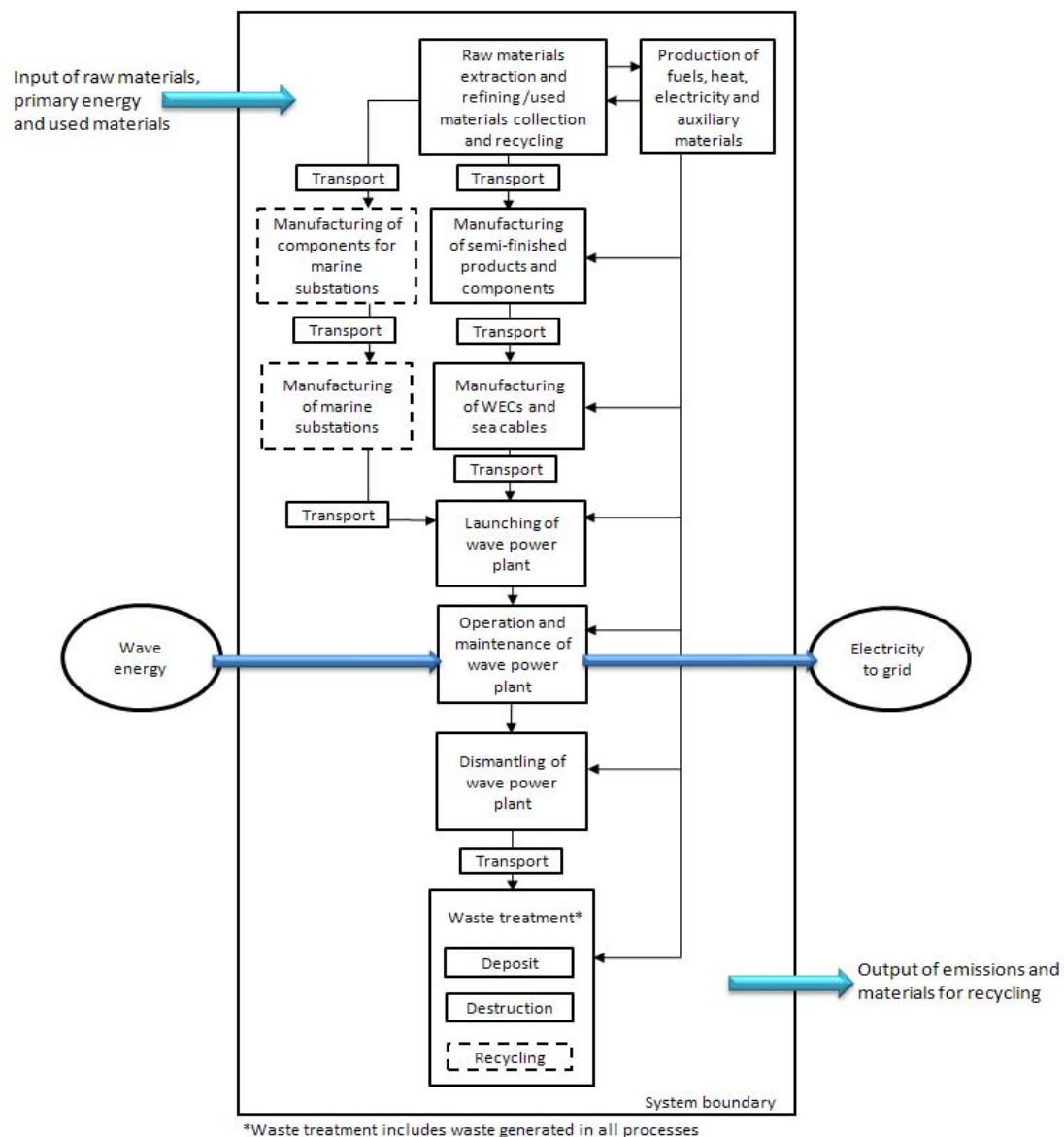


FIGURE 3: SIMPLIFIED PROCESS TREE WITH SYSTEM BOUNDARIES. SOLID LINES INDICATE INCLUDED PROCESSES WHEREAS DASHED LINES INDICATE PROCESSES EXCLUDED FROM THE STUDY. WASTE TREATMENT PROCESSES ARE INCLUDED FOR WASTES PRODUCED BY ALL INCLUDED PROCESSES.

Geographical and temporal boundaries and boundaries towards nature are defined as follows:

- No geographical boundary is set, meaning that emissions and inputs to and from nature and other technical systems are included disregarding geographical location.
- The temporal boundary for emissions to air and surface water from landfills is 100 years, since emissions after that time are considered negligible. Regarding emissions to groundwater no temporal boundary is set, meaning that long-term emissions are included in the inventory. All other inputs and outputs to and from the system are included disregarding when they take place.
- All emissions to nature from included processes and all inputs from nature are included.

3.2.4 ALLOCATION

The ISO standards for LCA recommend the use of system expansion as allocation method. The EPD® approach differs from the ISO standards in this respect. The PCR prescribes the use of allocation based on physical causal relationships. In the present study no allocation is needed regarding foreground data (all environmental impact of the wave power plant is allocated to the produced electricity). In the background data used (e.g. raw materials extraction) allocations are sometimes necessary. Background data calculated using system expansion is avoided as far as possible. If system expansion causes negative flows of e.g. emissions in background data these flows are set to zero, as prescribed in the PCR.

The approach used regarding waste and reused or recycled materials is important to define since it will have great impact on the results of an LCA study. It is basically a question of defining where materials enter and leave the studied system. The EPD guide lines prescribe using the “Polluter Pays” approach, which designates the environmental burden of waste as follows:

- The environmental impact connected to the treatment of wastes not being used by any subsequent user rests with the generator of the waste – hence, the waste is not considered as a resource.
- The environmental impact connected to the processing of the waste into a resource for a subsequent user rests with the user of the resulting resource (1).

The “Polluter Pays approach” is further illustrated in figure 3 by describing the handling of different types of wastes, worn-out products and output flows. Figures 4 and 5 specifically describe the PP allocation method applied to waste incineration and recycling respectively.

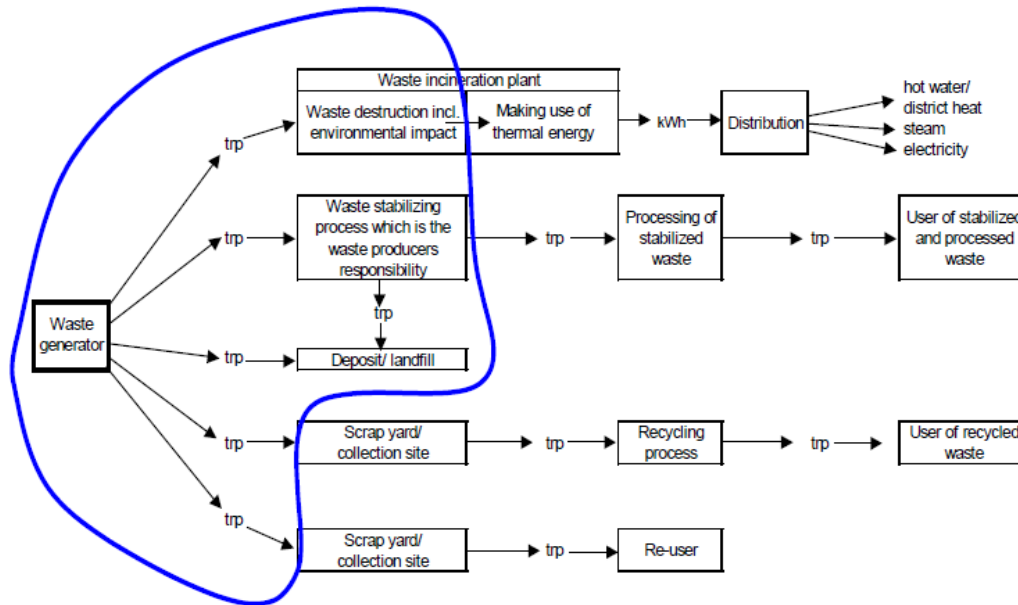


FIGURE 4: THE "POLLUTER PAYS" PRINCIPLE ILLUSTRATED FOR VARIOUS TYPES OF WASTE TREATMENT OPTIONS. THE ENCIRCLED AREA INDICATES THE ENVIRONMENTAL IMPACT THAT HAS TO BE CARRIED BY THE WASTE GENERATOR (9).

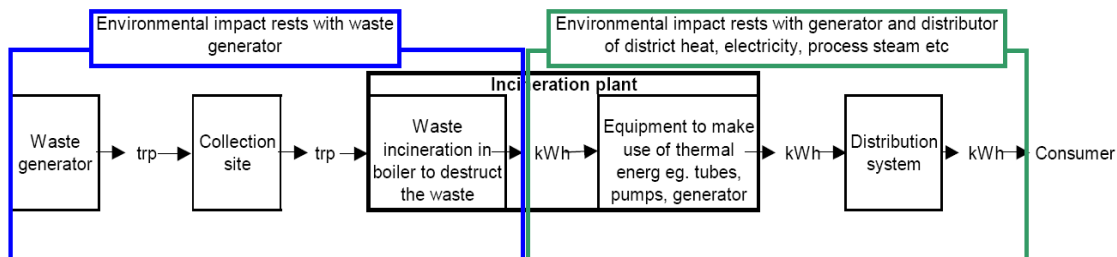


FIGURE 5: THE "POLLUTER PAYS" PRINCIPLE APPLIED TO WASTE INCINERATION AND RESULTING ENERGY PRODUCTS. ALL EMISSIONS DUE TO WASTE INCINERATION ARE ALLOCATED TO THE WASTE DESTRUCTION FUNCTION OF THE INCINERATION PLANT (9).

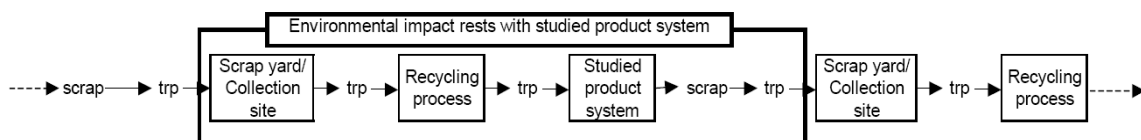


FIGURE 6: THE "POLLUTER PAYS" PRINCIPLE APPLIED TO INPUTS OF RECYCLED MATERIALS AND OUTPUTS OF MATERIALS THAT WILL BE RECYCLED. USED MATERIALS ENTER AND LEAVE THE STUDIED SYSTEM AT THE SCRAP YARD/COLLECTION SITE. THUS USED MATERIALS AND SCRAP FOR RECYCLING RESPECTIVELY REPRESENT INPUT AND OUTPUT FROM THE SYSTEM. NO ENVIRONMENTAL BURDENS FROM EARLIER LIFE CYCLES OR CREDITS FOR CONSEQUENT LIFE CYCLES ARE ASSIGNED TO THE STUDIED SYSTEM (9).

3.2.5 ENVIRONMENTAL IMPACT CATEGORIES

The choice of environmental impact categories is done according to the PCR. Impact categories are divided into material use and potential environmental impact.

Material use includes:

- **Non-renewable resources**
 - Material resources
 - Energy resources (used for energy conversion purposes)
- **Renewable resources**
 - Material resources
 - Energy resources (used for energy conversion purposes)
- **Water use**

Potential environmental impact includes:

- **Emission of greenhouse gases** (expressed as the sum of global warming potential, GWP, 100 years, in CO₂ equivalents).
- **Emission of ozone-depleting gases** (expressed as the sum of ozone-depleting potential in CFC 11-equivalents, 20 years).
- **Emission of acidifying gases** (expressed as the sum of acidifying potential in SO₂ equivalents).*
- **Emission of gases that contribute to the creation of ground-level ozone** (expressed as the sum of ozone-creating potential, ethene-equivalents).
- **Emission of substances to water contributing to oxygen depletion** (eutrophication, expressed as the sum of oxygen consumption potential in PO₄ equivalents)*

Characterization factors used in the study are prescribed in GPI Annex B and presented in appendix 3. These characterization factors are widely accepted and used within the scientific community. *Regarding acidification and eutrophication potential the GPI prescribes that the potential be presented as mol H⁺ and kg O₂ respectively. However, the characterization factors given relate the listed substances to SO₂- and PO₄-equivalents.

3.2.6 CUT-OFF CRITERIA

The general rule for omitting inventory data of negligible relevance to the study is that for the overall inventory results 99% of the elementary flows regarding mass, energy content and environmental impact shall be included in the LCA.

3.2.7 DATA QUALITY REQUIREMENTS - SPECIFIC AND GENERIC DATA

The GPI classifies data into three categories:

- **specific data** are data gathered from actual production sites and product-specific processes.
- **selected generic data** are data from commonly available sources, prescribed by the PCR, fulfilling prescribed characteristics regarding reference year, cut-off criteria, completeness and representativeness
- **other generic data** are data from other generic data sources

The GPI states that environmental impact associated with other generic data must not exceed 10% of the total environmental impact. According to the PCR, generic data (selected or other) should not be older than 10 years. Specific data shall be used if available. For the operational phase, data shall always be specific. Since no full-scale wave power plants yet exist, the present LCA study is performed for a “typical” plant, as it is planned to be designed, constructed and operated.

Specific data is used for

- material composition of the wave power plant
- some transportation distances
- deployment and dismantling of the plant (consumption of ship fuel)
- maintenance processes and reinvestment rates

Generic data is used for

- manufacture of construction- and auxiliary materials (such as fuels, lubrication oil etc.)
- some transportation distances
- transportation services (fuel use and emissions in conjunction with transportation)
- waste treatment processes
- regional mixes for electricity generation
- resource use and emissions in conjunction with electricity used during the construction/reinvestment/dismantling processes

4 SYSTEM DESCRIPTION

4.1 DESCRIPTION OF WAVE ENERGY CONVERTER

A wave energy converter of the studied type consists to a large part of steel and iron. The translator body is made of cast iron whereas the buoy, the wire, the stator, the support structure and the casing is mainly made of various types of steel. The permanent magnets on the translator are made of a neodymium-iron-boron alloy (about 24, 75 and 1% respectively). The stator cables consist of copper wire insulated with cross-linked polyethylene (PEX). The wave energy converter is attached to a foundation. The design and material for the foundation is a matter under discussion. For the prototypes made so far, armed concrete foundations have been used and this type of foundation is also assumed to be used in the present study.

4.2 PLANT LAYOUT

No wave power plants of the studied type yet exist. Further, the work with designing wave energy converters for serial production is not completed. Hence, this LCA is conducted for a hypothetical wave power plant (WPP) consisting of “prototype” generators. In reality the design of generators used in full scale WPPs is expected to be considerably “slimmed down”, thus increasing the material efficiency and environmental performance of the technology.

The studied WPP consists of 1000 generators, placed in arrays of 50 units. Each array is connected by a sea cable to a low voltage marine substation (LVMS) which in turn is connected to a medium voltage substation (MVMS). In the LVMS, the irregular power from the generators is converted into a DC voltage and then into a smooth, three-phase AC voltage. The voltage is then transformed to 12 kV in the LVMS and further to 36 kV in the MVMS. From the MVMS the power from the generators is transmitted by a sea cable to the electrical grid on shore. The distance from the WPP to the grid is assumed to be 10 km. Figure 7 is a schematic diagram of the electrical system of a plant.

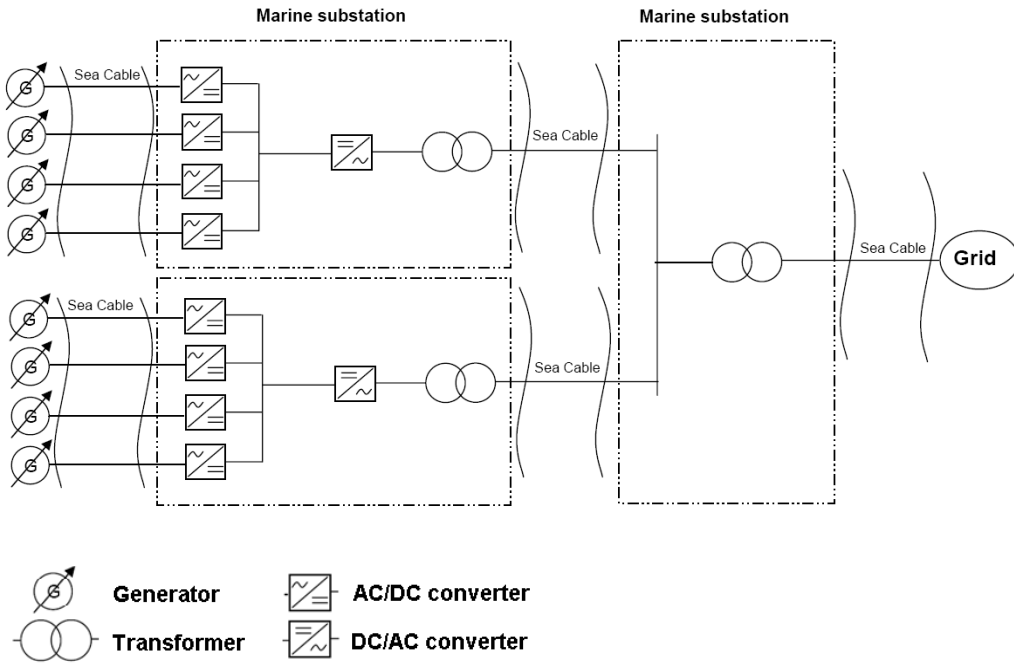


FIGURE 7. SCHEMATIC IMAGE OF THE ELECTRICAL SYSTEM OF A WPP (1).

4.3 ELECTRICITY PRODUCTION

The energy delivered to the grid E_{grid} from a wave power plant is calculated as follows:

$$E_{\text{grid}} = J_{\text{avg}} \times D \times \text{Abs} \times \eta_{\text{gen}} \times A_v \times \eta_{\text{trans}} \times N \times \text{Life} \times 8760 \text{ [kWh]}$$

where

J_{avg} = average power flow of the waves [kW/m wavefront]

D = buoy diameter [m]

Abs = average power absorption rate

η_{gen} = generator efficiency

A_v = availability factor

η_{trans} = transmission efficiency

N = number of WECs

Life = technical service life of the WPP [years]

The power absorption rate is the percentage of the incoming power flow that is absorbed by the buoy. The availability factor stems from the assumption that all WECs are not functioning 100% of the time. The transmission efficiency is the efficiency of the marine substations and sea cables transmitting the electricity to the on shore grid connection .

4.4 DESCRIPTION OF STUDIED CASES

Two cases, referred to as Case NO and Case SE, are studied. The two cases reflect a wave power plant operating off the coast of Norway and Sweden respectively. The parameter values shown in table 1 are the same for both cases. The total delivered energy and reference flows corresponding to the functional units are presented for the two cases in table 2.

The average power flow of the waves and the distance from the production site in Lysekil to the WPP site is different for the two cases. The two cases also differ in that a larger ship is assumed to be used to transport the WECs to the plant site in the Norwegian case. This means that the ship is able to carry a larger number of WECs, thus needing fewer trips to and from Lysekil, but also that the fuel consumption of the ship is larger.

- **Case NO** is a WPP (as described above) operating in a location with an average wave climate of 20 kW/meter wavefront. This wave climate can be found off the coast of Norway, at least 400 km by ship from Lysekil. The distance used in the study is 650 km. The ship used for transport to the WPP site is assumed to carry 100 WECs at a time and to consume 30 tons of marine diesel oil per day (24h). The average power absorption rate is assumed to be 12,5%.
- **Case SE** is a WPP operating in a relatively poor wave climate, with an average power flow of 5 kW/meter wavefront. This wave climate is found off the Swedish west coast, near Lysekil. The distance for ship transportation used in the study is 30 km. The ship used for transport to the WPP site is assumed to carry 40 WECs at a time and to consume 20 tons of marine diesel oil per day (24h). The average power absorption rate is assumed to be 15%.

The power absorption rate is an important factor and is difficult to estimate. The absorption depends on the wave period (the time between two wave crests) as well as generator design and load properties. The absorption decreases with longer wave periods. The power flow of the waves are proportional to the wave period times the square of the wave height, meaning that a larger power flow generally means longer wave periods and lower absorption rates. This is one of the reasons why the absorption rate is lower in the Norwegian case.

The generators used in a wave power plant will be designed for the wave climate of the plant site. However, at the present stage only one complete generator design exists and this

design is used for both cases in the study. This generator is designed for the Swedish west coast. To reflect this, the absorption rate is adjusted a bit further downwards for the Norwegian case.

TABLE 1: PARAMETERS USED TO CALCULATE ENERGY OUTPUT FROM A WPP, USED IN CASES NO AND SE

Parameter	Value
Number of WECs	1000
Buoy diameter	4 m
Generator efficiency	85 %
Availability factor	99 %
Power consumption for operation of WPP	40 kW
Estimated technical life of WEC	20 years
Distribution efficiency	95 %

TABLE 2: TOTAL DELIVERED ENERGY AND REFERENCE FLOWS CORRESPONDING TO THE FUNCTIONAL UNIT

	Case NO	Case SE
Delivered energy to grid [TWh/WPP]	1,33	0,395
Reference flow [WPP/kWh to grid]	$7,52 \times 10^{-10}$	$2,53 \times 10^{-9}$

4.4 DEPLOYMENT, MAINTENANCE AND DISMANTLING OF THE PLANT

The manufacturing of the wave power plant will take place at the seaside in Lysekil and the WECs will be loaded directly onto a specially built ship that will carry them to the WPP site for deployment. Deployment of the plant is estimated to take two hours per WEC. Each WEC is also assumed to need on average two hours of maintenance work and one replacement of the wire rope throughout its lifetime. Dismantling of the plant will basically be done by the same procedure as the deployment.

5 METHODOLOGY

5.1 DATA COLLECTION

5.1.1 BACKGROUND DATA

Life cycle inventory data for materials/semi-finished products (e.g. copper wire, steel profiles), construction and dismantling services, transports and waste treatment are generic data collected from the sources listed in table 3, along with references for more information about the data. The data sources are further described in appendix 1. In some cases other sources than those prescribed in the PCR were used. This was done mainly because data for some materials and processes were not provided by the prescribed data sources.

TABLE 3: BACKGROUND DATA SOURCES. *OTHER THAN PRESCRIBED IN THE PCR

Material/process	Source	Reference
<i>Metals</i>		
Aluminium	European Aluminium Association	(11)
Copper wire	Deutsches Kupferinstitut	(12)
Neodymium	Ecoinvent	(13)
Steel/iron	Worldsteel	(14)
Stainless steel	World stainless	(15)
Zinc	Ecoinvent	(16)
Other	Ecoinvent	(17)
<i>Concrete</i>	Ecoinvent	(18)
<i>Plastics and rubber</i>		
ABS	PlasticsEurope, through Ecoinvent	(19)
EPDM rubber	Ecoinvent*	(20)
EVA	Ecoinvent*	(20)
GAP (Glass fibre reinforced plastic)	Ecoinvent*	(18)
Polyethylene (HDPE, PEX, LDPE, LLDPE)	PlasticsEurope, through Ecoinvent	(20)
Polyamide 6	PlasticsEurope, through Ecoinvent	(20)
Polypropylene	PlasticsEurope, through Ecoinvent	(20)
Polyurethane	Ecoinvent*	(20)
<i>Chemicals</i>		
Lubricating oil	Ecoinvent*	(13)
Paints	Ecoinvent*	(13)
Other chemicals	Ecoinvent*	(13)
<i>Other materials</i>	Ecoinvent	(17)
<i>Transports</i>		
Road	NTM, Nätverket för Trafik och Miljön	(21)
Rail	NTM/Ecoinvent*	(21)/ (22)
Air	Ecoinvent*	(22)
Sea	Ecoinvent*	(22)
Production of ship fuel	Ecoinvent	(23)
Combustion of ship fuel	SMED, Svenska MiljöEmissionsData	(24)
<i>Electricity</i>	Ecoinvent (electricity mixes from IEA)	(25)
<i>Manufacturing processes</i>		
Cleaning and blasting of cast iron	CPM LCA database*	(26)
Other manufacturing processes	Ecoinvent	(16), (20),(27)
<i>Waste treatment processes</i>	Ecoinvent	(28)

5.1.2 ECOINVENT LCI DATABASE

The Ecoinvent LCI database is prescribed in the PCR as source for selected generic data for a number of materials and processes. The database was developed by the Swiss Centre for Life Cycle Inventories, which is a cooperation between a number of Swiss LCA institutions. The database contains about 4000 datasets for products, services and processes, presented as national, regional or global averages. The Ecoinvent methodology is based on a modular approach, and data are neither aggregated horizontally nor vertically, meaning that different processes producing the same output are presented separately, as are subsequent steps in a process chain. System expansion is not used in the Ecoinvent data. More information on the Ecoinvent database can be found in (17).

Most data in the Ecoinvent database reflect average European conditions. An important exception is electricity production, for which data is provided by country and by voltage level. For manufacturing processes that are assumed to take place in Sweden the electricity mix used in the Ecoinvent processes was changed to the Swedish electricity mix. For a few processes assumed to take place in Germany the German electricity mix was used, whereas the average European electricity mix was used for processes taking place in an unknown (European) location.

5.1.3 MATERIAL COMPOSITION

The material composition of components produced specifically for the wave power plant (most of the WECs, casing and support structures in marine substations) has mainly been derived from CAD drawings. In most cases component weights were given in the drawings (calculated by the CAD program). Some weights were calculated manually based on dimensions and material densities. For off-the-shelf components (wire ropes, sea cables, electrical components in marine substations) the material content was calculated and/or estimated from data in product sheets.

Amounts of materials removed by milling and drilling are estimations based on drawings. When such estimations were not possible a standard amount from Ecoinvent was used (0,23 kg metal removed by milling per kg finished product).

5.1.4 TRANSPORTS

Figure 8 shows an overview of the transports included in the LCA. Transportation distances for semi-finished products and components to the WEC production site were estimated in the cases where the production site is known. In other (quite numerous) cases, standard distances were used. The distances were taken from the Ecoinvent Overview and Methodology report (17), with the exception of an adjustment upwards of the transport distance of semi-finished steel products, done to reflect the geographical location of Swedish and European steel works in relation to Lysekil. The distances are shown in table 4.

All background data for materials and semi-finished products include transports to the European production site or regional storage. For the transport from these sites to component manufacturing sites the standard distances in table 4 have been used. Regarding

transportation of waste to scrap yards, deposit or incineration sites the standard distance 100 km has been used for all materials.

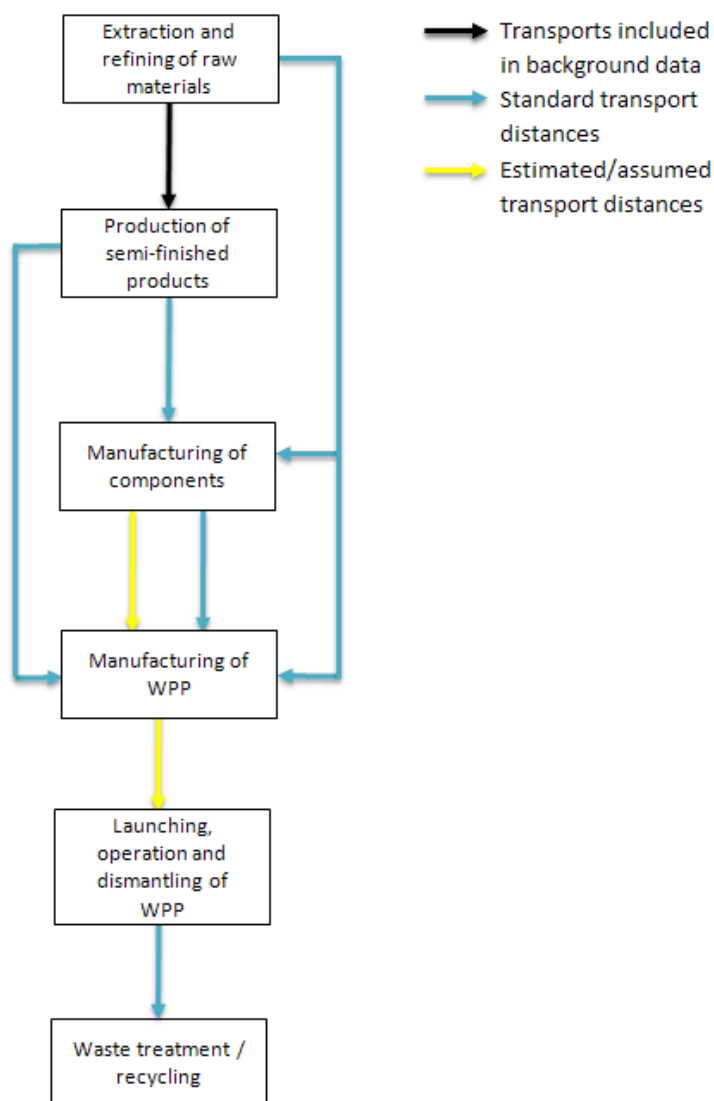


FIGURE 8: OVERVIEW OF TRANSPORTATION DISTANCES USED IN THE LCA

TABLE 4: STANDARD TRANSPORTATION DISTANCES USED FOR MATERIALS, SEMI-FINISHED PRODUCTS AND COMPONENTS FOR USE IN EUROPE.

Material	Train [km]	Lorry [km]
Chemicals	600	100
Concrete	-	50
Steel	350	150
Other metals	200	100
Nitrogen	200	100
Plastics	200	100

The prescribed data source for transports is NTM (Nätverket för trafik och miljön / Swedish Network for Traffic and the Environment) or regional alternatives. NTM provides transport data reflecting Swedish conditions. The NTM data for road transport (lorry) was assumed to reflect average European conditions and was used for all road transport. Regarding transport by train the mix of electro traction and diesel engines as well as the electricity production mix varies widely between countries. Therefore NTM data was used for transports within Sweden whereas data for European rail transports was taken from the Ecoinvent database. Data for intercontinental air and sea transport (used for import of some components) was also taken from Ecoinvent.

5.1.5 SHIP OPERATIONS

The transport of the WECs and other components to the WPP site is assumed to be done using a ship built especially for this purpose and the ship is not assumed to carry any other cargo when returning to Lysekil. The NTM data, which is based on average utilization levels of freight ships, is therefore not directly applicable. The source used in the present study is a report from Svenska MiljöEmissionsData (SMED) (24), which is one of the data sources used by NTM. The data is given per ton of consumed fuel. Data on speed and fuel consumption per hour for a ship that may be used was provided by the shipping company. The fuel consumption as well as the emission factors differ between the transportation phase and the working phase and this is reflected in the data. In the Norwegian case the fuel consumption rate for transportation was approximated by fuel consumption rates for larger cargo ships.

5.1.6 APPROXIMATIONS AND SIMPLIFICATIONS

The following approximations were made because of lacking data:

- Production of cast iron was approximated by production of secondary steel (produced from steel scrap in an electric arc furnace).
- All stainless steel grades have been approximated by data for grade 316 stainless steel.
- Drawing of aluminium wire (for transformers) was approximated by extrusion of aluminium profiles.
- Cold forming of steel dished ends was approximated by cold rolling of steel.
- The data for copper wire was given per meter of wire with a cross-section area of 1 mm². The environmental impact of copper wire was assumed to be equally large per kg of wire regardless of the wire size.
- NdFeB magnets material composition and production (through a sintering process) was approximated by the production of neodymium oxide and iron sinter.
- The process of extruding plastic insulation on to conductors was approximated by extrusion of plastic pipes.
- Crosslinked polyethylene (PEX) was approximated by high-density polyethylene (HDPE, from which PEX is made).

- Cutting of stator steel sheets and manufacturing of dummy loads, bearings, nuts and bolts have been approximated by the Ecoinvent process "steel product manufacturing" including resource consumption and emissions from an average metal working machine.
- The material composition of some electrical components has been approximated by the material composition of a circuit breaker (31).

Simplifications made in the study mainly concern manufacturing processes. For instance, the production of cables only include the processes of producing copper wire, extruding plastics on to the wire, drawing and zinc coating of steel wire (for reinforcement). The manufacturing of WECs from semi-finished products include the following processes:

Cleaning and blasting (steel, cast iron)
 Cold forming (steel pressure vessel heads)
 Cutting (stator steel sheets, approximated by "steel product manufacturing")
 Drilling (steel, cast iron, aluminium)
 Extrusion (plastics, rubber)
 Milling (steel, cast iron)
 Manufacturing of dummy loads, bearings, nuts and bolts (approximated by "steel product manufacturing")
 Pipe drawing (production of seamless steel pipes)
 Welding (steel)
 Wire drawing (production of steel wire from wire rod)
 Zinc coating (steel)

For launching, maintenance and dismantling processes only the production and combustion of marine diesel oil is considered. Processes excluded from the study are deemed to be of negligible importance for the results.

5.2 SIMAPRO LCA SOFTWARE TOOL

The life cycle of the WPP was modelled using the SimaPro LCA software tool. SimaPro was developed by the Dutch consultant company PRé Consultants and is one of the most widely used LCA software tools. The SimaPro license includes the Ecoinvent database, which was one of the main reasons for the choice of software.

SimaPro is based on a modular approach to LCA, using unit processes representing a quantitative amount of output from a process. Each unit process contains input from nature or technosphere (other unit processes) and output of products and emissions. The unit process can also contain output of waste for treatment, which is linked to waste treatment unit processes. For instance, the unit process "Hard coal, burned in industrial furnace" represents the environmental impact from the combustion of 1 MJ of hard coal. Emissions from the combustion are included as elementary flows, whereas the coal production is included as 0,035 kg of the unit process "Hard coal mix, at regional storage". The use of electricity and transports are included as corresponding amounts of unit processes. The combustion process also includes the disposal of hard coal ash, represented by 0,0029 kg of the unit process "Disposal of hard coal ash to residual material landfill".

The elementary flows to and from the unit processes are characterized into environmental impact categories using characterization factors defined in the chosen environmental impact assessment method. The assessment methods can be modified by the user. The system of unit processes, is represented in a process tree or network. The relative or absolute contribution of each unit process to the various environmental impact categories can be seen in the network or in a process contribution table. The resulting elementary flows are presented in an inventory table. The software also provides the possibility to compare processes or systems and by using parameters different scenarios can be modelled.

With SimaPro uncertainty calculations can be carried out using Monte Carlo analysis. Monte Carlo analysis is a statistical method for assessing the combined variation of data points added together, each with different standard deviations. For each data point a mean value, a coefficient of variance and a statistical distribution is given. A random value within the defined distribution interval is generated for all data points, resulting in a new value for the sum of the data points. By repeating this process n times a data set consisting of n values for the sum is obtained. The mean value and standard deviation of this data set is then calculated. More information on SimaPro can be found in (32) and at the PRé Consultants website (33).

5.3 UNCERTAINTY ESTIMATIONS

Most of the data in the Ecoinvent database is supplied as a mean value with a log-normal distribution defined by the square of the geometric standard deviation. The 95% confidence interval is then obtained by multiplying or dividing the mean value with the geometric standard deviation. However, in many cases the data sources have not provided any uncertainty data and instead a simplified standard procedure has been used to quantify the uncertainty of this data. A qualitative assessment of the data quality was made using a pedigree matrix (see table 5), giving the data an indicator score for each of six characteristics: reliability, completeness, temporal correlation, geographical correlation, further technological correlation and sample size. The indicator scores were then translated into uncertainty factors (table 6) based on expert judgement. Further, a basic uncertainty factor (table 7) was assigned to each data point depending on the type of input or output. These factors are also based on expert judgement and derive from the fact that some flows show larger variations. For instance, emissions of CO₂ from a combustion process can be calculated quite accurately from the carbon content of the fuel, whereas emissions of heavy metals or CO are largely dependent on combustion properties. These seven uncertainty factors are then combined to calculate the square of the geometric standard deviation (SD²) through the following formula:

$$SD^2 = e^{\sqrt{(\ln U_1)^2 + (\ln U_2)^2 + (\ln U_3)^2 + (\ln U_4)^2 + (\ln U_5)^2 + (\ln U_6)^2 + (\ln U_7)^2}}$$

where

U_1 = uncertainty factor of reliability

U_2 = uncertainty factor of completeness

U_3 = uncertainty factor of temporal correlation

U_4 = uncertainty factor of geographical correlation

U_5 = uncertainty factor of further technological correlation

U_6 = uncertainty factor of sample size

U_b = basic uncertainty factor

TABLE 5: PEDIGREE MATRIX USED TO EVALUATE DATA QUALITY, ADAPTED FROM (17).

Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
Temporal correlation	Less than 3 years of difference from the reference period	Less than 6 years of difference from the reference period	Less than 10 years of difference from the reference period	Less than 15 years of difference from the reference period	Age of data unknown or more than 15 years of difference to the reference period
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area		Data from unknown or distinctly different area
Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials, but same technology, OR data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
Sample size	>100, continuous measurement, balance of purchased products	>20	>10	≥3	Unknown

TABLE 6: DEFAULT UNCERTAINTY FACTORS TO BE COMBINED WITH THE PEDIGREE MATRIX (17).

Indicator score	1	2	3	4	5
Reliability	1,00	1,05	1,10	1,20	1,50
Completeness	1,00	1,02	1,05	1,10	1,20
Temporal correlation	1,00	1,03	1,10	1,20	1,50
Geographical correlation	1,00	1,01	1,02		1,10
Further technological correlation	1,00		1,20	1,50	2,00
Sample size	1,00	1,02	1,05	1,10	1,20

TABLE 7: BASIC UNCERTAINTY FACTORS (17).

	Basic uncertainty factor
Input	
Thermal energy, electricity, semi-finished products, working material, waste treatment services, primary energy carriers, metals, salts	1,05
Transport services	2
Emissions to water	
COD, inorganic compounds (NH ₄ , PO ₄ , NO ₃ , Cl, Na etc.)	1,5
PAH	3
Heavy metals	5
Emissions to air	
CO ₂ , SO ₂	1,05
NMVOC, Nox, N ₂ O, CH ₄ , NH ₃	1,5
Particulates, PAH	3
CO, heavy metals	5
Other inorganic emissions	1,5

The data sources used in the present study for steel and copper products do not provide any uncertainty data. Therefore the pedigree matrix method used by Ecoinvent has been applied to assess the uncertainty of this data. The pedigree matrix and uncertainty factors used are the same as those used by Ecoinvent, shown in tables 5-7. The indicator scores given the data sets for steel products were (2,2,2,1,1,1) and for copper wire (2,2,2,1,3,1). The higher value of the "further technological correlation" uncertainty factor for copper wire stems from the fact that the environmental impact per kg of wire is assumed to be the same for all wire sizes.

Regarding standard transportation distances Ecoinvent uses the value of 2,09 for the square of the geometrical standard deviation. The same value was used when standard distances were used in the present study. The uncertainty regarding fuel consumption for ship operations was modelled as a uniform distribution with minimum and maximum deviating by 20% from the mean.

In the Monte Carlo analysis of the final results 1000 calculations were done for each impact category. The resulting uncertainty reflects uncertainties in background data and does not take into account uncertainty due to lacking data or any uncertainty in foreground data such as e.g. material composition. Also, no uncertainty of the characterization factors used is considered.

6 RESULTS

6.1 INVENTORY ANALYSIS

Table 8 shows the amounts of materials used per wave energy converter and per wave power plant. Besides the large amounts of concrete used for foundations, steel constitutes the main part of the constructions. The wave energy converters contribute to almost 99% of the total material flows of a wave power plant.

TABLE 8: AMOUNTS OF MATERIALS USED IN PER WAVE ENERGY CONVERTER AND PER WAVE POWER PLANT

Material	Weight per WEC [kg]	Weight per WPP [tonnes]
Concrete	50200	50400
Steel	12600	13100
Cast iron	1800	1800
Stainless steel	244	245
Copper	189	240
NdFeB-magnets	180	180
Plastics and rubber	166	218
Paint	75	76
Zinc	40	44
Aluminium	17	40
Transformer oil, lubrication oil, other chemicals	8	22
Sum	65519	66365

Figure 9 is a SimaPro network visualization of the processes needed to produce 1 kWh of wave power electricity delivered to the grid. In this case, the relative contribution to the use of non-renewable energy is shown for each process, with a cut-off rate of 6% for showing processes in the network (no cut-off rate is applied for including processes in the calculations).

TABLE 9: CALCULATED INPUT OF MATERIALS AND ENERGY RESOURCES PER KWH OF ELECTRICITY DELIVERED TO THE GRID. LINES IN ITALIC REPRESENT AGGREGATED FLOWS.

Input	Unit	Amount per kWh delivered to grid [g]	
		Case NO	Case SE
Material resources			
Renewable			
Air	g	3,05	10,3
Carbon dioxide, in air	g	0,32	1,06
Oxygen, in air	g	0,03	0,10
Water	m3	0,06	0,22
Non-renewable			
Bauxite	g	0,14	0,47
Calcite	g	3,01	10,2
Cerium, 24% in bastnasite, 2.4% in crude ore	g	0,03	0,10
Chromium ore, in ground	g	0,04	0,13
Clay, unspecified	g	1,10	3,70
Copper ore	g	7,94	26,8
Dolomite	g	0,24	0,82
Gravel	g	31,3	106
Inert rock	g	0,49	1,65
Iron, in ground	g	14,1	47,5
Limestone	g	0,88	2,98
Sodium chloride, in ground	g	0,33	1,10
Zinc	g	0,09	0,30
Recycled materials			
Iron scrap	g	5,07	17,1
Energy			
Renewable			
Energy, from wood	MJ	6,69E-05	2,26E-04
Energy, geothermal	MJ	1,38E-06	4,65E-06
Energy, gross calorific value, in biomass	MJ	3,51E-03	1,18E-02
Energy, gross calorific value, in biomass, primary forest	MJ	1,06E-05	3,58E-05
Energy, kinetic (in wind)	MJ	2,66E-04	8,73E-04
Energy, solar	MJ	2,00E-05	6,70E-05
Energy, potential (in hydropower reservoir)	MJ	9,12E-03	3,06E-02
Energy, renewable, unspecified	MJ	8,93E-03	3,01E-02
Sum	MJ	0,02	0,07
Non-renewable			
Energy from coal	MJ	0,23	0,78
Energy from natural gas	MJ	0,07	0,22
Energy from oil	MJ	0,17	0,53
Energy from uranium	MJ	0,03	0,09
Energy, non-renewable, unspecified	MJ	0,01	0,05
Sum	MJ	0,52	1,69

TABLE 10: CALCULATED EMISSIONS CONTRIBUTING TO IMPACT CATEGORIES. LINES IN ITALIC REPRESENT AGGREGATED FLOWS.

Emissions contributing to impact categories	Amount per kWh delivered to grid [g]	
	Case NO	Case SE
<i>Emissions to air</i>		
Carbon dioxide	37,1	122,8
Methane	0,028	0,091
Halogenated hydrocarbons	1,36E-04	4,56E-04
NOx (as NO2)	0,119	0,362
Sox (as SO2)	0,087	0,284
Aromatic hydrocarbons	1,55E-04	5,06E-04
Alcohols	6,97E-05	2,32E-04
Aldehydes	7,19E-05	2,34E-04
Alkanes (except methane)	8,91E-04	2,81E-03
Ammonium salts	3,64E-09	1,22E-08
Acetic acid	1,14E-04	3,79E-04
Acetone	4,73E-05	1,59E-04
Ammonia	0,005	0,017
Ammonium, ion	5,34E-13	1,80E-12
Chloroform	1,72E-09	5,63E-09
Dinitrogen monoxide	1,68E-03	5,17E-03
Ethene	3,34E-05	1,03E-04
Ethyl acetate	1,84E-04	6,03E-04
Ethyne	5,70E-07	1,91E-06
Formic acid	6,93E-07	2,32E-06
Hydrocarbons, unspecified	4,32E-04	1,46E-03
Isoprene	9,12E-09	3,02E-08
Methyl ethyl ketone	1,84E-04	6,04E-04
Methyl formate	1,80E-12	6,03E-12
Nitrate	1,46E-08	4,83E-08
Nitric oxide	1,70E-09	5,74E-09
NMVOC, non-methane volatile organic compounds	0,011	0,030
Phosphorus	2,48E-06	8,39E-06
Propene	2,78E-05	8,41E-05
Propionic acid	3,39E-07	1,11E-06
Sulfur hexafluoride	2,80E-07	9,28E-07
t-Butyl methyl ether	2,72E-09	9,16E-09
<i>Emissions to water</i>		
Ammonia	1,98E-08	6,68E-08
Ammonium, ion	0,001	0,003
COD, Chemical Oxygen Demand	0,088	0,251
Nitrate	0,005	0,017
Nitrite	5,00E-05	1,69E-04
Nitrogen	0,003	0,010
Phosphate	0,001	0,003
Phosphorus	4,20E-05	1,41E-04
<i>Emissions to soil</i>		
Ammonia	2,47E-06	8,32E-06
Phosphorus	4,04E-06	1,37E-05

TABELL 11: OUTPUT TO TECHNOSPHERE. LINES IN ITALIC REPRESENT AGGREGATED FLOWS.

Output to technosphere	Amount per kWh delivered to grid [g]	
	Case NO	Case SE
Waste		
<i>Nuclear waste</i>	4,37E-04	1,48E-03
Waste water	2,11E-14	7,11E-14
<i>Other waste</i>	16,6	56,1
Materials for recycling		
Steel	11,58	39,06
Copper	0,18	0,60
Concrete	38	127
Aluminium	0,03	0,10

6.2 ENVIRONMENTAL IMPACT ASSESSMENT

The potential environmental impacts, energy and water use resulting from the SimaPro calculations are presented in tables 11 and 12. The most conspicuous result is the long energy payback time in the Swedish case. The energy payback time is the time needed for the wave power plant to produce the amount of energy that was used to construct it. Considering that the lifetime of the plant is assumed to be twenty years, it is obvious that future generator designs need to be slimmed down considerably to be viable.

The 95% confidence intervals are based on Monte Carlo analysis and reflect uncertainties in background data and transportation distances. No uncertainty is assumed to be associated with the material composition of the plant or the amount of electricity produced. The variation due to these factors are roughly reflected by the varying results for the different power absorption rates presented in tables 11 and 12. The results used for contribution- and sensitivity analysis are marked with light grey.

TABLE 12: POTENTIAL ENVIRONMENTAL IMPACT, ENERGY AND WATER USE AND ENERGY PAYBACK TIME AT DIFFERENT POWER ABSORPTION RATES, CASE NO. *WATER USE DOES NOT INCLUDE WATER THROUGH TURBINES IN HYDROPOWER PLANTS. **THE UNCERTAINTY OF THE ENERGY PAYBACK TIME IS APPROXIMATED BY THE WEIGHTED MEAN OF THE UNCERTAINTIES FOR RENEWABLE AND NON-RENEWABLE ENERGY.

Case NO				95% confidence
Absorption [%]	10	12,5	15	interval
GWP [kg CO2 eq/kWh]	0,048	0,039	0,032	± 5%
ODP [kg CFC-11 eq/kWh]	1,85E-09	1,48E-09	1,23E-09	± 48%
eq/kWh]	1,85E-05	1,48E-05	1,23E-05	± 15%
Acidification [kg SO2 eq/kWh]	1,99E-04	1,60E-04	1,33E-04	± 11%
Eutrophication [kg PO4 eq/kWh]	2,93E-05	2,34E-05	1,95E-05	± 19%
Non renewable energy [MJ/kWh]	0,645	0,516	4,30E-01	± 7%
Renewable energy [MJ/kWh]	0,027	0,021	1,78E-02	± 17%
Water use [m3/kWh]	7,08E-04	5,67E-04	4,72E-04	± 7%
Total energy delivered [kWh]	1,07E+09	1,33E+09	1,60E+09	-
Energy payback time [years]	3,7	3,0	2,5	± 7%

TABLE 13: POTENTIAL ENVIRONMENTAL IMPACT, ENERGY AND WATER USE AND ENERGY PAYBACK TIME AT DIFFERENT POWER ABSORPTION RATES, CASE SE. *WATER USE DOES NOT INCLUDE WATER THROUGH TURBINES IN HYDROPOWER PLANTS. **THE UNCERTAINTY OF THE ENERGY PAYBACK TIME IS APPROXIMATED BY THE WEIGHTED MEAN OF THE UNCERTAINTIES FOR RENEWABLE AND NON-RENEWABLE ENERGY.

Case SE				95% confidence
Absorption [%]	12,5	15	17,5	interval
GWP [kg CO2 eq/kWh]	0,152	0,126	0,108	± 5%
ODP [kg CFC-11 eq/kWh]	5,50E-09	4,58E-09	3,93E-09	± 50%
eq/kWh]	5,64E-05	4,70E-05	4,03E-05	± 15%
eq/kWh]	5,97E-04	4,97E-04	4,26E-04	± 12%
Eutrophication [kg PO4 eq/kWh]	8,45E-05	7,04E-05	6,03E-05	± 19%
Non renewable energy [MJ/kWh]	2,028	1,690	1,45E+00	± 8%
Renewable energy [MJ/kWh]	0,087	0,072	6,19E-02	± 16%
Water use [m3/kWh]	2,28E-03	1,90E-03	1,63E-03	± 7%
Total energy delivered [kWh]	3,28E+08	3,95E+08	4,63E+08	-
Energy payback time [years]	11,7	9,8	8,4	± 8%

7 INTERPRETATION

7.1 CONTRIBUTION ANALYSIS

Figure 10 shows the relative contribution from different product stages to the impact categories. It is clear that the construction of the wave power plant is the most important production stage, with a relative contribution ranging from 63 to 99% of the potential environmental impact and resource use. The deployment, operation and maintenance and end-of-life phase are dominated by ship operations. The total contribution from these phases ranges from less than one to over forty percent.



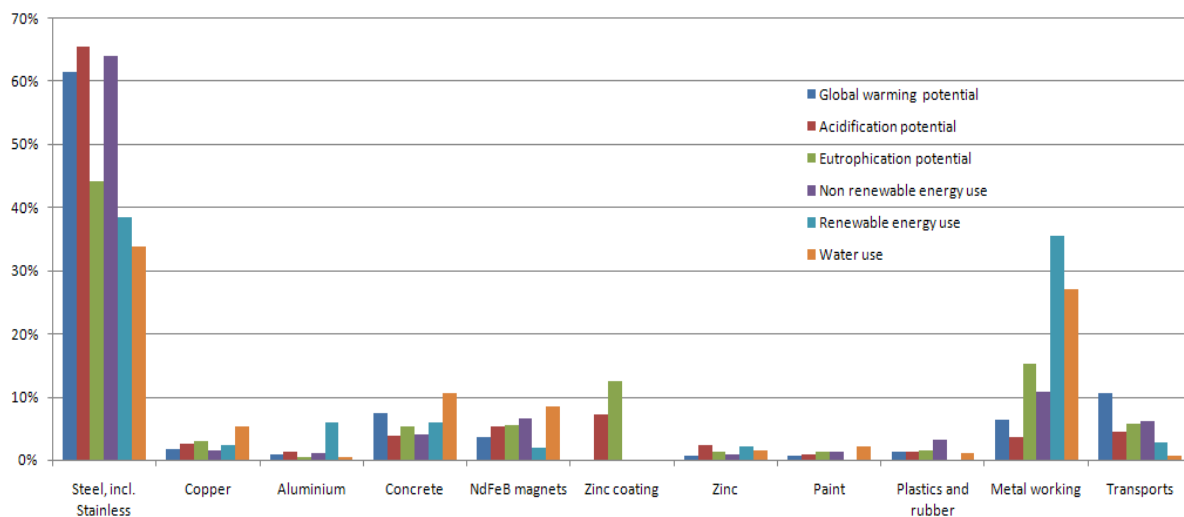
FIGUR 10. RELATIVE CONTRIBUTION OF DIFFERENT PRODUCT STAGES TO THE ENVIRONMENTAL IMPACT CATEGORIES

The WPP construction stage is further broken down into different processes in figure 11. Only six impact categories are presented in the figure. The reason for this is that the inventory data for steel does not include emissions of ozone depleting gases or gases contributing to the forming of ground level ozone. With this in mind it is probable that the results for these impact categories are underestimated. The lacking data for some impact categories in some datasets will of course also have an impact on the results presented in figure 10 above. Input data quality is further discussed in chapter 7.3.

It is obvious that the production of steel is the single most important factor. Metal working processes also have a relatively large impact. The large contributions to renewable energy use and water use from metal working processes consist mainly of hydropower and water used in ancillary processes respectively.

The relative contribution from concrete and neodymium-iron-boron-magnets is of about the same magnitude, though 50 tons of concrete and only 180 kg magnets is used for each WEC. The environmental impact from the magnets stems mainly from the production of neodymium oxide, though only about 25% of the magnets consists of neodymium.

The transports presented in figure 10 do not include transports associated with the production of raw materials and semi-finished products. In other words, transports represented by the black arrow in figure 7 (chapter 5) are included in the bars for material production.



FIGUR 11: PROCESS CONTRIBUTION TO POTENTIAL ENVIRONMENTAL IMPACT AND RESOURCE CONSUMPTION FOR THE CONSTRUCTION OF THE WPP. THE PROCESSES SHOWN REPRESENT 88-98% OF THE ENVIRONMENTAL IMPACT.

7.2 SENSITIVITY ANALYSIS

The impacts of the following assumptions were assessed in a sensitivity analysis:

- **The weight of the concrete foundation for the WECs** was assumed to be 50 tons. The weight of the foundations is an issue which is not quite settled and could vary as much as 25 tons in each direction. The weight of the foundation constitutes a large part of the WEC weight and will affect transportation and waste treatment needs besides the production of the concrete itself.
- **All metals and all concrete were assumed to be recycled** at the end of the WPP life cycle. The impacts of this assumption was assessed by creating an alternative waste treatment scenario, where all materials were sent to incineration or landfill.

- **The average time needed for maintenance work** was assumed to be two hours per WEC. In the sensitivity analysis the impact was investigated of doubling the maintenance time.
- **The distance from the production site in Lysekil to the WPP site** was assumed to be 650 km in the Norwegian case. In the sensitivity analysis this distance was adjusted by 250 km in both directions, the relative change in environmental impact representing a distance span from 400-900 km.
- **The approximation of cold forming and cutting of steel** by cold rolling and "steel product manufacturing" might, based on the contribution analysis, have a significant impact on the final results. By adjusting the environmental impact stemming from these processes by 50% it is assumed that a "worst case scenario" is modelled regarding the importance of these approximations.

The results of the sensitivity analysis are presented in table 13. The sensitivity analysis was carried out for both the Norwegian and the Swedish case, except regarding the distance to the production site. Since the results were very similar for both cases only the results for case NO is presented. Most of the relative changes in environmental impacts are well within the 95% confidence intervals presented in tables 11 and 12 (chapter 6). The impact of not recycling the wave power plant at the end of its life cycle is very small for most impact categories. Expanding the system boundaries would however increase the importance of recycling, since the recycled materials will replace virgin materials in subsequent life cycles. This is not reflected in the present study. The increased environmental impact of the alternative waste scenario consists of emissions and resource use associated with waste incineration and landfills.

The approximations made regarding cold forming of steel pressure vessel heads and cutting of stator sheet might, as can be seen in table 13, have a rather large impact on the final results concerning energy and water use.

TABLE 14: RESULTS OF THE SENSITIVITY ANALYSIS

Relative change	Case NO ±25 t concrete	Case NO No recycling	Case NO 4 h maintenance	Case NO ±250 km dist to Lysekil	Case NO ±50% impact from cold forming and cutting of steel
GWP	±3%	0%	3%	±1%	±3%
ODP	-3%	1%	9%	±3%	±5%
Photochemical oxidation	±4%	5%	7%	±3%	±2%
Acidification	±2%	2%	7%	±3%	±1%
Eutrophication	±3%	4%	8%	±4%	±2%
Non renewable energy	±2%	0%	3%	±1%	±4%
Renewable energy	±3%	1%	0%	0%	±13%
Energy, total	±2%	0%	3%	±1%	±5%
Water use	±5%	2%	1%	0%	±8%

7.3 CONSISTENCY CHECK

7.3.1 GEOGRAPHICAL, TEMPORAL AND TECHNOLOGICAL COVERAGE

The background data used in the study in many cases reflect average European conditions. This is not a problem regarding materials such as e.g. steel and copper since these products are traded across national (and regional) borders. Concrete is a material that is not traded across long distances. The Ecoinvent data set for concrete reflects Swiss production and has been modified by using the Swedish electricity mix instead of the Swiss. The same was done regarding production processes taking place in Sweden, for which only datasets reflecting average European conditions were available. The overall assessment is that no major problems regarding geographical coverage are associated with the LCA results.

All background data sources do not fulfill the requirement of not being more than ten years old. However, the relative contribution of these data (concerning some plastics and parts of the NTM transport dataset) is estimated to be well below 1%, based on the contribution analysis.

The approximations regarding manufacturing processes described in chapter 5.1.6 also have an impact on the results. This impact is estimated to be negligible, with the possible exception of the approximations regarding cold forming of steel and cutting of stator sheet, which were assessed in the sensitivity analysis. These approximations are however considered to be the best that could be done with available data. In conclusion, the technology coverage is judged to be adequate in relation to the goal and scope of the study.

7.3.2 DATA QUALITY

Generic data was collected from selected sources with a few exceptions. Based on the contribution analysis, data from "other generic sources" are not estimated to contribute to more than a few percents of the final results. Thus the study well complies with the GPI requirement that less than 10% of the environmental impact should stem from "other generic data".

There are a few issues regarding the selected generic data sources which probably affect the LCA results. The most important of these is the fact that the Worldsteel data does not include ozone depleting gases (ODP) or gases contributing to the formation of ground-level ozone (photochemical oxidation). Some of the latter substances are nevertheless included in the data, since they also contribute to other impact categories. Emissions of ODP-gases from the WPP life cycle mainly stem from the production of crude oil. Steel production constitutes about 20% of the total crude oil used in the WPP life cycle, roughly indicating that 20% of ODP-gases are unaccounted for in the study. However, the data used in the study are a few years old, and the use of ozone depleting substances has decreased steadily in the last decade, suggesting that the emissions of these substances are overestimated in the study. The conclusion is simply that the results for these two categories are hefted with large uncertainties.

The steel data also contains some waste flows not followed to the grave, constituting most of the waste flows listed in table 10. Some untreated waste flows also stem from the data for aluminium, but these waste flows are very small compared to those associated with steel production. Treatment of this waste is not included in the study, meaning an underestimation of the environmental impact. This effect is however expected to be very small, considering that waste treatment processes constitute a very small part of the final results and that the steel production waste consists mainly of inert mining waste (rock) (14).

7.4 COMPLETENESS CHECK

Of the total weight of the WPP more than 99,9% is estimated to be included in the study, including all materials associated with large environmental impact per unit mass. The manufacturing of marine substations is not included in the study. The "amounts" of manufacturing processes is proportional to the amounts of materials used. Considering that the substations constitute less than 0,5% of the materials used in the WPP it is not likely that the exclusion of marine substation manufacturing processes will affect the final results by more than about 0,1%. The importance of other processes that were neglected, such as painting of steel parts, assembling of components and use of e.g. lubricant oil in ship engines, are also estimated to be of the negligible magnitude. The Ecoinvent database is known to be conservative in its assumptions and environmental impact stemming from Ecoinvent data is thus not assumed to be underestimated.

The overall assessment is that the study complies to the 1% cut-off rule regarding mass flows as well as potential environmental impact and resource use.

8 CONCLUSIONS AND OUTLOOK

As with non-fuel based electricity production in general, the environmental impact of wave power stems mainly from the plant construction phase. Thus, the amounts of materials used in the construction of the wave power plant are of great importance for the plants' environmental performance. Wave power at the present stage of development uses relatively large amounts of materials per kWh of produced electricity. In particular, steel production contributes to a large part of the environmental impact, ranging from about thirty to almost sixty percent of the results for the various impact categories. New designs of wave energy converters for serial production are estimated to reduce the amounts of steel by as much as fifty percent, indicating that the environmental performance of this wave power concept can be improved significantly.

Though concrete constitutes about 75% of the materials used in the wave power plant, the relative contribution of concrete to the overall results is at most about ten percent. Reducing the amounts of concrete used may be important from an economical point of view, but is not as important an environmental factor. It is also worth noting that the production of neodymium-iron-boron permanent magnets contributes to almost as much of the potential environmental impact as the production of concrete, though the magnets make up less than 0,3% of the total weight of used materials.

The sensitivity analysis indicated that recycling of used material at the end of the WPP life cycle does not decrease the environmental impact of the system significantly. Of course, in a wider perspective this is not true. The recycled materials will substitute virgin materials in subsequent products, reducing the energy use and environmental impact of their life cycles. This is a weakness of the modular approach to LCA used in the present study.

Though most of the potential environmental impacts stem from material use, the deployment, maintenance and disassembly phases are not of negligible importance. The environmental impact of these phases could be decreased significantly e.g. by transporting the wave energy converters by train, using biofuel for the ships and decreasing the time needed for work out at sea.

The present life cycle assessment was performed for a hypothetical wave power plant, involving many assumptions and estimations. In the future, LCA studies of existing plants will provide more reliable results. Also, as wave power technology matures, LCA studies will produce results that are comparable to those for other energy conversion technologies. This is the most obvious possible improvement of the study. Other possibilities include the improvement of background data, by e.g. collecting data from specific sites of component and material production, which was not practicable within the time frame of this master's degree project. Improvement of generic databases will of course also increase the reliability of this type of study.

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APPENDIX 1: DESCRIPTION OF BACKGROUND DATA SOURCES

TABLE A11: DESCRIPTION OF BACKGROUND DATA SOURCES

Source	Reference year	Geographical coverage	Production coverage	Allocation methods
EAA, European Aluminium Association	2005	EU 27 + EFTA average	≥ 90% of primary Al production, 33% of extrusion output	Mass / system expansion
Deutsches Kupfer-institut	2000	EU 25 average	> 95% of	Market value/ system expansion
Worldsteel	2005	EU 15 average	60% of	Market value/ net calorific value/ system expansion
World stainless	2005	European average	Unknown	Market value/ net calorific value/ system expansion
PlasticsEurope	1996-1999	European average	Unknown	Element content /mass / system expansion
NTM, Nätverket för trafik och miljö	1997-1999	Swedish average	Unknown / not applicable	Unknown
Cooper, Gustavsson (emissions from combustion of ship fuels)	2002	Swedish average	(Measurements from 62 ships, > 180 engines)	No allocation
CPM LCA database (cleaning and sand blasting of cast iron)	2002	SKF Mekan AB, Katrineholm, Sweden	Site specific	Mass
Ecoinvent	2000-2005 (with exceptions)	Varying	Varying	Physical and economic causal relationships

APPENDIX 2: INVENTORY TABLES

TABLE A21: INPUT OF NATURAL RESOURCES PER KWH OF PRODUCED ELECTRICITY FROM WAVE POWER

Input of natural resources	Unit	Case NO	Case SE
Air	kg	0,0037062	0,0125074
Aluminium, 24% in bauxite, 11% in crude ore, in ground	kg	1,768E-06	5,964E-06
Anhydrite, in ground	kg	2,264E-09	7,636E-09
Barite, 15% in crude ore, in ground	kg	5,194E-07	1,752E-06
Barium sulphate	kg	3,275E-18	1,105E-17
Basalt, in ground	kg	2,503E-07	8,448E-07
Bauxite, in ground	kg	0,0001405	0,000474
Borax, in ground	kg	9,038E-11	3,048E-10
Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	kg	2,123E-08	7,166E-08
Calcite, in ground	kg	0,0030119	0,0101635
Calcium chloride	kg	3,334E-16	1,125E-15
Carbon dioxide, in air	kg	0,0003044	0,0010258
Carbon, in organic matter, in soil	kg	1,531E-07	5,166E-07
Cerium, 24% in bastnasite, 2.4% in crude ore, in ground	kg	3,004E-05	0,0001014
Chromium ore, in ground	kg	3,87E-05	0,0001306
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	kg	1,91E-07	6,442E-07
Chrysotile, in ground	kg	5,534E-09	1,867E-08
Cinnabar, in ground	kg	5,433E-10	1,833E-09
Clay, bentonite, in ground	kg	3,86E-07	1,299E-06
Clay, unspecified, in ground	kg	0,0010952	0,003696
Coal, brown (lignite)	kg	3,855E-05	0,0001301
Coal, brown, in ground	kg	0,0004779	0,001594
Coal, hard, unspecified, in ground	kg	0,0072943	0,0246058
Cobalt, in ground	kg	8,257E-11	2,475E-10
Colemanite ore	kg	8,498E-11	2,868E-10
Colemanite, in ground	kg	4,545E-06	1,534E-05
Copper ore, in ground	kg	0,0079445	0,02681
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	3,508E-09	1,183E-08
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	kg	3,913E-09	1,319E-08
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	kg	1,038E-09	3,499E-09
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	kg	2,768E-08	9,339E-08
Diatomite, in ground	kg	1,883E-14	6,329E-14
Dolomite, in ground	kg	0,0002435	0,0008217
Energy, from coal	MJ	0,0014696	0,0049594
Energy, from coal, brown	MJ	0,0011495	0,0038791
Energy, from gas, natural	MJ	0,0022582	0,0076207

Input of natural resources	Unit	Case NO	Case SE
Energy, from oil	MJ	0,0077287	0,026082
Energy, from uranium	MJ	0,0010164	0,0034301
Energy, from wood	MJ	6,686E-05	0,0002256
Energy, geothermal	MJ	1,378E-06	4,65E-06
Energy, gross calorific value, in biomass	MJ	0,0033754	0,011378
Energy, gross calorific value, in biomass, primary forest	MJ	1,062E-05	3,581E-05
Energy, kinetic (in wind), converted	MJ	0,0002971	0,0009947
Energy, non-renewable, unspecified	MJ	0,0134056	0,0452398
Energy, potential (in hydropower reservoir), converted	MJ	0,0087864	0,0296044
Energy, renewable	MJ	0,0089333	0,030147
Energy, solar	MJ	1,732E-05	5,845E-05
Energy, solar, converted	MJ	3,442E-06	1,151E-05
Europium, 0.06% in bastnasite, 0.006% in crude ore, in ground	kg	7,527E-08	2,54E-07
Feldspar, in ground	kg	3,789E-09	1,279E-08
Ferromanganese	kg	1,59E-20	5,367E-20
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	kg	4,786E-09	1,558E-08
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	kg	3,373E-09	1,113E-08
Fluorspar, 92%, in ground	kg	2,45E-07	8,098E-07
Fluorspar, in ground	kg	1,015E-06	3,425E-06
Gadolinium, 0.15% in bastnasite, 0.015% in crude ore, in ground	kg	1,879E-07	6,339E-07
Gallium, 0.014% in bauxite, in ground	kg	1,248E-18	4,083E-18
Gas, mine, off-gas, process, coal mining/m3	m3	6,167E-06	2,071E-05
Gas, natural (0,8 kg/m3)	m3	0,0009137	0,0030834
Gas, natural, in ground	m3	0,0009453	0,0031354
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	kg	1,453E-12	4,903E-12
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	kg	2,664E-12	8,99E-12
Gold, Au 1.4E-4%, in ore, in ground	kg	3,19E-12	1,076E-11
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	kg	4,872E-12	1,644E-11
Gold, Au 4.3E-4%, in ore, in ground	kg	1,208E-12	4,075E-12
Gold, Au 4.9E-5%, in ore, in ground	kg	2,892E-12	9,76E-12
Gold, Au 6.7E-4%, in ore, in ground	kg	4,478E-12	1,511E-11
Gold, Au 7.1E-4%, in ore, in ground	kg	5,049E-12	1,704E-11
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	kg	3,025E-13	1,021E-12
Granite, in ground	kg	1,136E-11	3,835E-11
Gravel, in ground	kg	0,0313315	0,1057337
Gypsum, in ground	kg	3,921E-08	1,323E-07
Heavy spar (barytes)	kg	2,467E-07	8,325E-07
Helium, 0.08% in natural gas, in ground	kg	6,303E-18	2,061E-17
Ilmenite, in ground	kg	1,511E-10	5,098E-10
Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	kg	3,537E-10	1,194E-09
Inert rock	kg	0,0004898	0,001653
Iron ore, in ground	kg	7,147E-05	0,0002412
Iron, 46% in ore, 25% in crude ore, in ground	kg	8,195E-05	0,0002765

Input of natural resources	Unit	Case NO	Case SE
Iron, in ground	kg	0,0139453	0,0470609
Kaolin ore	kg	3,423E-11	1,155E-10
Kaolinite, 24% in crude ore, in ground	kg	1,724E-08	5,813E-08
Kieserite, 25% in crude ore, in ground	kg	5,21E-11	1,757E-10
Lanthanum, 7.2% in bastnasite, 0.72% in crude ore, in ground	kg	9,007E-06	3,039E-05
Lead - zink ore (4,6%-0,6%)	kg	2,03E-08	6,851E-08
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	kg	6,303E-07	2,127E-06
Lead, in ground	kg	3,187E-20	1,075E-19
Limestone, in ground	kg	0,0008835	0,0029816
Magnesite, 60% in crude ore, in ground	kg	1,023E-06	3,451E-06
Magnesium chloride leach (40%)	kg	3,187E-08	1,075E-07
Magnesium, 0.13% in water	kg	3,992E-12	1,347E-11
Manganese ore, in ground	kg	4,434E-06	1,496E-05
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	kg	2,359E-08	7,96E-08
Metamorphous rock, graphite containing, in ground	kg	1,493E-09	5,036E-09
Molybdenite (Mo 0,24%)	kg	6,905E-09	2,33E-08
Molybdenum ore, in ground	kg	6,699E-06	2,261E-05
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	kg	5,144E-10	1,736E-09
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	kg	1,364E-11	4,597E-11
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	kg	8,464E-09	2,854E-08
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	kg	4,996E-11	1,684E-10
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	kg	1,707E-08	5,757E-08
Neodymium, 4% in bastnasite, 0.4% in crude ore, in ground	kg	4,954E-06	1,672E-05
Nickel ore, in ground	kg	2,221E-05	7,495E-05
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	kg	8,084E-09	2,725E-08
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	kg	2,076E-07	7,002E-07
Nitrogen, in air	kg	6,917E-11	2,334E-10
Occupation, arable, non-irrigated	m2a	1,38E-06	4,658E-06
Occupation, construction site	m2a	1,794E-07	6,029E-07
Occupation, dump site	m2a	9,398E-06	3,166E-05
Occupation, dump site, benthos	m2a	5,808E-11	1,911E-10
Occupation, forest, intensive	m2a	2,785E-06	9,395E-06
Occupation, forest, intensive, normal	m2a	6,73E-05	0,0002269
Occupation, forest, intensive, short-cycle	m2a	2,663E-06	8,984E-06
Occupation, industrial area	m2a	7,829E-07	2,595E-06
Occupation, industrial area, benthos	m2a	5,321E-13	1,751E-12
Occupation, industrial area, built up	m2a	1,312E-08	4,423E-08
Occupation, industrial area, vegetation	m2a	6,777E-09	2,285E-08
Occupation, mineral extraction site	m2a	8,92E-05	0,000301
Occupation, permanent crop, fruit, intensive	m2a	5,17E-06	1,744E-05

Input of natural resources	Unit	Case NO	Case SE
Occupation, shrub land, sclerophyllous	m2a	2,016E-07	6,801E-07
Occupation, traffic area, rail embankment	m2a	1,795E-10	5,807E-10
Occupation, traffic area, rail network	m2a	1,985E-10	6,421E-10
Occupation, traffic area, road embankment	m2a	7,109E-07	2,397E-06
Occupation, traffic area, road network	m2a	7,005E-10	2,297E-09
Occupation, urban, discontinuously built	m2a	2,676E-14	8,751E-14
Occupation, water bodies, artificial	m2a	3,005E-05	0,0001013
Occupation, water courses, artificial	m2a	5,836E-06	1,966E-05
Oil, crude, in ground	kg	0,0038095	0,0116945
Olivine, in ground	kg	1,217E-09	4,104E-09
Oxygen, in air	kg	3,015E-05	0,0001018
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	3,478E-12	1,029E-11
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	8,358E-12	2,473E-11
Peat, in ground	kg	2,564E-05	8,653E-05
Phosphate ore, in ground	kg	8,763E-13	2,957E-12
Phosphorus minerals	kg	2,806E-10	9,47E-10
Phosphorus pentoxide	kg	1,001E-17	3,379E-17
Phosphorus, 18% in apatite, 12% in crude ore, in ground	kg	2,731E-08	9,117E-08
Phosphorus, 18% in apatite, 4% in crude ore, in ground	kg	1,914E-08	6,232E-08
Potassium chloride	kg	8,026E-11	2,708E-10
Praseodymium, 0.42% in bastnasite, 0.042% in crude ore, in ground	kg	5,256E-07	1,774E-06
Precious metal ore	kg	3,423E-10	1,155E-09
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	7,334E-14	2,142E-13
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	2,629E-13	7,68E-13
Pumice, in ground	kg	3,305E-12	1,115E-11
Renewable fuels, unspecified	kg	6,55E-14	2,211E-13
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	7,285E-14	2,128E-13
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	2,282E-13	6,664E-13
Rhenium, in crude ore, in ground	kg	1,063E-13	3,117E-13
Samarium, 0.3% in bastnasite, 0.03% in crude ore, in ground	kg	3,751E-07	1,266E-06
Sand, quartz, in ground	kg	6,924E-06	2,337E-05
Sand, unspecified, in ground	kg	2,243E-07	7,57E-07
Shale, in ground	kg	6,413E-09	2,163E-08
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	kg	3,206E-11	1,082E-10
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground	kg	2,286E-11	7,714E-11
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	kg	2,111E-12	7,122E-12
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	kg	4,82E-12	1,627E-11
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	kg	4,725E-12	1,594E-11
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	kg	3,117E-12	1,052E-11
Slate, in ground	kg	2,945E-19	9,938E-19

Input of natural resources	Unit	Case NO	Case SE
Sodium chloride, in ground	kg	0,000326	0,0010998
Sodium nitrate, in ground	kg	1,544E-13	5,209E-13
Sodium sulfate	kg	1,257E-10	4,242E-10
Sodium sulphate, various forms, in ground	kg	2,39E-06	8,059E-06
Soil, unspecified, in ground	kg	1,393E-06	4,7E-06
Stibnite, in ground	kg	1,957E-15	6,577E-15
Sulfur, bonded	kg	2,732E-14	9,221E-14
Sulfur, in ground	kg	2,094E-06	7,066E-06
Sylvite, 25 % in sylvinitite, in ground	kg	8,627E-07	2,911E-06
Talc, in ground	kg	3,34E-08	1,127E-07
Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	kg	2,53E-11	8,537E-11
Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	kg	3,429E-12	1,157E-11
Tin ore, in ground	kg	2,83E-19	9,549E-19
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	kg	2,776E-09	9,37E-09
TiO ₂ , 54% in ilmenite, 2.6% in crude ore, in ground	kg	1,493E-07	4,94E-07
TiO ₂ , 95% in rutile, 0.40% in crude ore, in ground	kg	2,502E-11	8,442E-11
Titanium ore, in ground	kg	2,148E-09	7,249E-09
Transformation, from arable	m ²	6,576E-10	2,218E-09
Transformation, from arable, non-irrigated	m ²	2,55E-06	8,604E-06
Transformation, from arable, non-irrigated, fallow	m ²	2,095E-10	7,066E-10
Transformation, from dump site, inert material landfill	m ²	1,218E-08	4,109E-08
Transformation, from dump site, residual material landfill	m ²	1,638E-08	5,523E-08
Transformation, from dump site, sanitary landfill	m ²	2,032E-09	6,847E-09
Transformation, from dump site, slag compartment	m ²	9,71E-09	3,277E-08
Transformation, from forest	m ²	1,999E-08	6,744E-08
Transformation, from forest, extensive	m ²	6,259E-07	2,111E-06
Transformation, from forest, intensive, clear-cutting	m ²	9,511E-08	3,208E-07
Transformation, from industrial area	m ²	5,023E-09	1,648E-08
Transformation, from industrial area, benthos	m ²	4,989E-15	1,642E-14
Transformation, from industrial area, built up	m ²	6,823E-12	2,221E-11
Transformation, from industrial area, vegetation	m ²	1,164E-11	3,789E-11
Transformation, from mineral extraction site	m ²	2,62E-06	8,839E-06
Transformation, from pasture and meadow	m ²	7,789E-08	2,622E-07
Transformation, from pasture and meadow, intensive	m ²	2,081E-09	7,022E-09
Transformation, from sea and ocean	m ²	1,986E-10	6,652E-10
Transformation, from shrub land, sclerophyllous	m ²	7,674E-08	2,587E-07
Transformation, from tropical rain forest	m ²	9,511E-08	3,208E-07
Transformation, from unknown	m ²	1,074E-05	3,626E-05
Transformation, to arable	m ²	3,524E-08	1,182E-07
Transformation, to arable, non-irrigated	m ²	2,552E-06	8,611E-06
Transformation, to arable, non-irrigated, fallow	m ²	4,249E-09	1,434E-08
Transformation, to dump site	m ²	6,686E-08	2,251E-07
Transformation, to dump site, benthos	m ²	5,808E-11	1,911E-10
Transformation, to dump site, inert material landfill	m ²	1,218E-08	4,109E-08

Input of natural resources	Unit	Case NO	Case SE
Transformation, to dump site, residual material landfill	m2	1,638E-08	5,523E-08
Transformation, to dump site, sanitary landfill	m2	2,032E-09	6,847E-09
Transformation, to dump site, slag compartment	m2	9,71E-09	3,277E-08
Transformation, to forest	m2	2,618E-06	8,836E-06
Transformation, to forest, intensive	m2	1,854E-08	6,256E-08
Transformation, to forest, intensive, clear-cutting	m2	9,511E-08	3,208E-07
Transformation, to forest, intensive, normal	m2	5,288E-07	1,783E-06
Transformation, to forest, intensive, short-cycle	m2	9,511E-08	3,208E-07
Transformation, to heterogeneous, agricultural	m2	5,103E-12	1,676E-11
Transformation, to industrial area	m2	8,342E-09	2,755E-08
Transformation, to industrial area, benthos	m2	1,405E-10	4,741E-10
Transformation, to industrial area, built up	m2	1,492E-09	5,021E-09
Transformation, to industrial area, vegetation	m2	7,536E-11	2,532E-10
Transformation, to mineral extraction site	m2	8,75E-06	2,953E-05
Transformation, to pasture and meadow	m2	7,951E-11	2,598E-10
Transformation, to permanent crop, fruit, intensive	m2	7,278E-08	2,455E-07
Transformation, to sea and ocean	m2	4,989E-15	1,642E-14
Transformation, to shrub land, sclerophyllous	m2	4,029E-08	1,359E-07
Transformation, to traffic area, rail embankment	m2	4,177E-13	1,351E-12
Transformation, to traffic area, rail network	m2	4,591E-13	1,485E-12
Transformation, to traffic area, road embankment	m2	5,537E-09	1,867E-08
Transformation, to traffic area, road network	m2	7,818E-12	2,564E-11
Transformation, to unknown	m2	2,492E-08	8,362E-08
Transformation, to urban, discontinuously built	m2	5,33E-16	1,743E-15
Transformation, to water bodies, artificial	m2	1,962E-06	6,619E-06
Transformation, to water courses, artificial	m2	7,223E-08	2,433E-07
Ulexite, in ground	kg	1,295E-11	4,371E-11
Uranium, in ground	kg	5,907E-08	1,986E-07
Water, cooling, unspecified natural origin/kg	kg	1,166E-06	3,933E-06
Water, cooling, unspecified natural origin/m3	m3	0,0001597	0,0005326
Water, lake	m3	1,64E-05	5,535E-05
Water, process and cooling, unspecified natural origin	m3	2,516E-05	8,492E-05
Water, river	m3	6,855E-05	0,0002302
Water, salt, ocean	m3	4,338E-06	1,423E-05
Water, salt, sole	m3	2,073E-06	6,072E-06
Water, turbine use, unspecified natural origin	m3	0,0609409	0,2052783
Water, unspecified natural origin/kg	kg	0,1883521	0,6356283
Water, unspecified natural origin/m3	m3	6,403E-05	0,000214
Water, well, in ground	m3	3,88E-05	0,0001309
Vermiculite, in ground	kg	2,031E-14	6,259E-14
Volume occupied, final repository for low-active radioactive waste	m3	1,113E-10	3,739E-10
Volume occupied, final repository for radioactive waste	m3	2,763E-11	9,287E-11
Volume occupied, reservoir	m3y	8,618E-05	0,0002899
Volume occupied, underground deposit	m3	5,155E-09	1,738E-08

Input of natural resources	Unit	Case NO	Case SE
Wood (16.9 MJ/kg)	kg	1,821E-09	6,144E-09
Wood, hard, standing	m3	8,521E-08	2,872E-07
Wood, primary forest, standing	m3	9,848E-10	3,322E-09
Wood, soft, standing	m3	2,295E-07	7,737E-07
Wood, unspecified, standing/m3	m3	1,038E-10	3,502E-10
Zinc ore, in ground	kg	1,065E-08	3,595E-08
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	kg	7,491E-05	0,0002528
Zinc, in ground	kg	1,483E-05	5,005E-05
Zirconium, 50% in zircon, 0.39% in crude ore, in ground	kg	3,48E-11	1,174E-10

TABLE A22: EMISSIONS TO AIR CONTRIBUTING TO ENVIRONMENTAL IMPACT CATEGORIES

Emissions to air	Unit	Case NO	Case SE
1-Propanol	kg	5,672E-18	1,855E-17
2-Propanol	kg	1,579E-10	5,329E-10
Acetaldehyde	kg	3,872E-09	1,299E-08
Acetic acid	kg	1,139E-07	3,839E-07
Acetone	kg	4,73E-08	1,596E-07
Ammonia	kg	5,201E-06	1,753E-05
Ammonium carbonate	kg	3,526E-12	1,189E-11
Ammonium nitrate	kg	4,628E-14	1,562E-13
Ammonium, ion	kg	5,341E-16	1,802E-15
Benzaldehyde	kg	8,513E-12	2,867E-11
Benzene	kg	9,165E-08	3,02E-07
Benzene, 1,2,4-trimethyl-	kg	4,81E-16	1,623E-15
Benzene, ethyl-	kg	4,14E-09	1,243E-08
Butane	kg	1,808E-07	5,42E-07
Butanol	kg	5,736E-10	1,936E-09
Carbon dioxide	kg	0,0221362	0,0747025
Carbon dioxide, fossil	kg	0,0156092	0,0489074
Carbon dioxide, land transformation	kg	1,574E-06	5,307E-06
Chloroform	kg	1,711E-12	5,759E-12
Cumene	kg	2,696E-08	9,092E-08
Cyclohexane	kg	3,01E-13	1,016E-12
Dinitrogen monoxide	kg	1,584E-06	5,181E-06
Ethane	kg	1,696E-07	5,489E-07
Ethane, 1,1-difluoro-, HFC-152a	kg	1,621E-16	5,302E-16
Ethane, 1,1,1-trichloro-, HCFC-140	kg	3,858E-14	1,301E-13
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	3,155E-12	1,061E-11
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	kg	1,939E-14	6,543E-14
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	4,877E-11	1,64E-10
Ethane, hexafluoro-, HFC-116	kg	3,312E-10	1,118E-09
Ethanol	kg	1,277E-09	4,24E-09
Ethene	kg	3,174E-08	1,04E-07
Ethene, tetrachloro-	kg	1,306E-07	4,408E-07
Ethyl acetate	kg	1,842E-07	6,215E-07
Ethyne	kg	5,707E-10	1,925E-09
Formaldehyde	kg	6,677E-08	2,251E-07

Emissions to air	Unit	Case NO	Case SE
Formic acid	kg	6,925E-10	2,336E-09
Heptane	kg	3,528E-08	1,036E-07
Hexane	kg	8,366E-08	2,492E-07
Hydrocarbons, unspecified	kg	4,322E-07	1,459E-06
Isoprene	kg	9,113E-12	3,074E-11
m-Xylene	kg	3,372E-10	1,136E-09
Methane	kg	1,099E-05	3,706E-05
Methane, biogenic	kg	9,938E-07	3,352E-06
Methane, bromo-, Halon 1001	kg	2,784E-18	9,396E-18
Methane, bromochlorodifluoro-, Halon 1211	kg	2,985E-11	1,003E-10
Methane, bromotrifluoro-, Halon 1301	kg	9,537E-11	2,819E-10
Methane, chlorodifluoro-, HCFC-22	kg	1,148E-10	3,86E-10
Methane, dichloro-, HCC-30	kg	2,039E-12	6,877E-12
Methane, dichlorodifluoro-, CFC-12	kg	4,285E-10	1,446E-09
Methane, dichlorofluoro-, HCFC-21	kg	1,264E-16	4,266E-16
Methane, fossil	kg	1,599E-05	5,213E-05
Methane, monochloro-, R-40	kg	1,347E-12	4,542E-12
Methane, tetrachloro-, CFC-10	kg	1,603E-10	5,407E-10
Methane, tetrafluoro-, CFC-14	kg	3,533E-09	1,192E-08
Methane, trichlorofluoro-, CFC-11	kg	2,052E-16	6,925E-16
Methane, trifluoro-, HFC-23	kg	4,022E-14	1,357E-13
Methanol	kg	6,666E-08	2,247E-07
Methyl ethyl ketone	kg	1,842E-07	6,215E-07
Methyl formate	kg	1,798E-15	6,067E-15
Nitrate	kg	1,459E-11	4,921E-11
Nitric oxide	kg	1,7E-12	5,736E-12
Nitrogen dioxide	kg	7,141E-16	2,41E-15
Nitrogen oxides	kg	0,0001275	0,0003671
NMVOC, non-methane volatile organic compounds	kg	9,673E-06	3,044E-05
Octane	kg	3,246E-11	1,095E-10
Pentane	kg	2,551E-07	7,772E-07
Phosphorus	kg	2,443E-09	8,24E-09
Propanal	kg	8,513E-12	2,867E-11
Propane	kg	2,051E-07	6,234E-07
Propene	kg	2,62E-08	8,53E-08
Propionic acid	kg	3,403E-10	1,146E-09
Styrene	kg	5,786E-11	1,951E-10
Sulfur dioxide	kg	2,404E-05	7,677E-05
Sulfur hexafluoride	kg	2,864E-10	9,599E-10
Sulfur oxides	kg	6,422E-05	0,0002082
t-Butyl methyl ether	kg	2,697E-12	9,101E-12
Toluene	kg	3,525E-08	1,092E-07

TABLE A23: EMISSIONS TO WATER CONTRIBUTING TO ENVIRONMENTAL IMPACT CATEGORIES

Substance	Unit	Case NO	Case SE
Ammonia	kg	1,98E-11	6,68E-11
Ammonium, ion	kg	9,26E-07	3,12E-06
COD, Chemical Oxygen Demand	kg	7,91E-05	2,51E-04
Nitrate	kg	4,95E-06	1,67E-05
Nitrite	kg	5,00E-08	1,69E-07
Nitrogen	kg	5,52E-07	1,86E-06
Nitrogen, total	kg	2,28E-06	7,69E-06
Phosphate	kg	9,27E-07	3,13E-06
Phosphorus	kg	4,14E-08	1,39E-07
Phosphorus, total	kg	5,45E-10	1,84E-09

TABLE A24: EMISSIONS TO SOIL CONTRIBUTING TO ENVIRONMENTAL IMPACT CATEGORIES

Substance	Unit	Case NO	Case SE
Ammonia	kg	2,47E-09	8,32E-09
Phosphorus	kg	3,88E-09	1,31E-08

APPENDIX 3: CHARACTERIZATION FACTORS

TABLE A31: CHARACTERIZATION FACTORS FOR SUBSTANCES CONTRIBUTING TO GLOBAL WARMING

Global warming (GWP100)			
Category	Substance	CAS-number	[kg CO2 eq/kg]
Air	1H,1H,2H,2H-Perfluorohexan-1-ol, HFE-7200	002043-47-2	55
Air	Benzaldehyde	000100-52-7	-0,092
Air	Butane, 1,1,1,3,3-pentafluoro-, HFC-365mfc	000406-58-6	890
Air	Butane, nonafluoromethoxy, HFE-7100	163702-07-6	390
Air	Butane, perfluoro-	000355-25-9	8600
Air	Butane, perfluorocyclo-, PFC-318	000115-25-3	10000
Air	Carbon dioxide	000124-38-9	1
Air	Carbon dioxide, fossil	000124-38-9	1
Raw	Carbon dioxide, in air	000124-38-9	-1
Air	Carbon dioxide, land transformation	000124-38-9	1
Air	Chloroform	000067-66-3	30
Air	Dimethyl ether	000115-10-6	1
Air	Dinitrogen monoxide	010024-97-2	296
Air	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	000075-68-3	2400
Air	Ethane, 1-chloro-2,2,2-trifluoro- (difluoromethoxy)-, HCFE-235da2	026675-46-7	340
Air	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	001717-00-6	700
Air	Ethane, 1,1-difluoro-, HFC-152a	000075-37-6	120
Air	Ethane, 1,1,1-trichloro-, HCFC-140	000071-55-6	140
Air	Ethane, 1,1,1-trifluoro-, HFC-143a	000420-46-2	4300
Air	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	000811-97-2	1300
Air	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	000076-13-1	6000
Air	Ethane, 1,1,2-trifluoro-, HFC-143	000430-66-0	330
Air	Ethane, 1,1,2,2-tetrafluoro-, HFC-134	000359-35-3	1100
Air	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	000076-14-2	9800
Air	Ethane, 1,2-difluoro-, HFC-152	000624-72-6	43
Air	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	002837-89-0	620
Air	Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC- 123	000306-83-2	120
Air	Ethane, chloropentafluoro-, CFC-115	000076-15-3	7200
Air	Ethane, fluoro-, HFC-161	000353-36-6	12
Air	Ethane, hexafluoro-, HFC-116	000076-16-4	11900
Air	Ethane, pentafluoro-, HFC-125	000354-33-6	3400
Air	Ethanol, 2,2,2-trifluoro-	000075-89-8	57
Air	Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2- trifluoroethyl-, HFE-347mcc3	000406-78-0	480
Air	Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2	000425-88-7	30
Air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf3	000382-34-3	430
Air	Ether, di(difluoromethyl), HFE-134	001691-17-4	6100
Air	Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245cb2	001885-48-9	580
Air	Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa2	001885-48-9	570
Air	Ether, ethyl 1,1,2,2-tetrafluoroethyl-, HFE- 374pc2	000512-51-6	540
Air	Ether, pentafluoromethyl-, HFE-125	003822-68-2	14900
Air	H-Galden 1040x		1800
Air	Hexane, perfluoro-	000355-42-0	9000
Air	HFE-236ca12 (HG-10)		2700

Air	HG-01		1500
Air	Methane	000074-82-8	23

Global warming (GWP100)

Category	Substance	CAS-number	[kg CO2 eq/kg]
Air	Methane, bromo-, Halon 1001	000074-83-9	5
Air	Methane, bromochlorodifluoro-, Halon 1211	000353-59-3	1300
Air	Methane, bromodifluoro-, Halon 1201	001511-62-2	470
Air	Methane, bromotrifluoro-, Halon 1301	000075-63-8	6900
Air	Methane, chlorodifluoro-, HCFC-22	000075-45-6	1700
Air	Methane, chlorotrifluoro-, CFC-13	000075-72-9	14000
Air	Methane, dibromo-	000074-95-3	1
Air	Methane, dichloro-, HCC-30	000075-09-2	10
Air	Methane, dichlorodifluoro-, CFC-12	000075-71-8	10600
Air	Methane, dichlorofluoro-, HCFC-21	000075-43-4	210
Air	Methane, difluoro-, HFC-32	000075-10-5	550
Air	Methane, fluoro-, HFC-41	000593-53-3	97
Air	Methane, fossil	000074-82-8	23
Air	Methane, iodotrifluoro-	002314-97-8	1
Air	Methane, monochloro-, R-40	000074-87-3	16
Air	Methane, tetrachloro-, CFC-10	000056-23-5	1800
Air	Methane, tetrafluoro-, CFC-14	000075-73-0	5700
Air	Methane, trichlorofluoro-, CFC-11	000075-69-4	4600
Air	Methane, trifluoro-, HFC-23	000075-46-7	12000
Air	Methane, trifluoro-methoxy-, HFE-143a		750
Air	Pentane, 2,3-dihydroperfluoro-, HFC-4310mee	138495-42-8	1500
Air	Pentane, perfluoro-	000678-26-2	8900
Air	Propane, 1,1,1,2,2,3-hexafluoro-, HFC-236cb	000677-56-5	1300
Air	Propane, 1,1,1,2,3,3-hexafluoro-, HFC-236ea	000431-63-0	1200
Air	Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea	000431-89-0	3500
Air	Propane, 1,1,1,3,3,3-pentafluoro-, HFC-245fa	000460-73-1	950
Air	Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa	000690-39-1	9400
Air	Propane, 1,1,1,3,3,3-hexafluoro-2-(fluoromethoxy)-		330
Air	Propane, 1,1,2,2,3-pentafluoro-, HFC-245ca	000679-86-7	640
Air	Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	000507-55-1	620
Air	Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	000422-56-0	180
Air	Propane, perfluoro-	000076-19-7	8600
Air	Propanol, 1,1,1,3,3,3-hexafluoro-2-	000920-66-1	190
Air	Propanol, pentafluoro-1-	000422-05-9	40
Air	Sulfur hexafluoride	002551-62-4	22200

TABLE A32: CHARACTERIZATION FACTORS FOR SUBSTANCES CONTRIBUTING TO OZONE LAYER DEPLETION

Ozone layer depletion (ODP)			
Category	Substance	CAS-number	[kg CFC-11 eq/kg]
Air	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	000075-68-3	0,14
Air	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	001717-00-6	0,33
Air	Ethane, 1,1,1-trichloro-, HCFC-140	000071-55-6	0,45
Air	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	000076-13-1	0,59
Air	Ethane, 1,2-dibromotetrafluoro-, Halon 2402	000124-73-2	11
Air	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	002837-89-0	0,08
Air	Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	000306-83-2	0,08
Air	Methane, bromo-, Halon 1001	000074-83-9	2,3
Air	Methane, bromochlorodifluoro-, Halon 1211	000353-59-3	9
Air	Methane, bromotrifluoro-, Halon 1301	000075-63-8	10,5
Air	Methane, chlorodifluoro-, HCFC-22	000075-45-6	0,14
Air	Methane, tetrachloro-, CFC-10	000056-23-5	1,23
Air	Methane, trichlorofluoro-, CFC-11	000075-69-4	1
Air	Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	000507-55-1	0,11
Air	Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	000422-56-0	0,1

TABLE A33: CHARACTERIZATION FACTORS FOR SUBSTANCES CONTRIBUTING TO PHOTOCHEMICAL OXIDATION

Photochemical oxidation			
Category	Substance	CAS-number	[kg C ₂ H ₄ -eq/kg]
Air	1-Butanol	000071-36-3	0,62
Air	1-Butene	000106-98-9	1,079
Air	1-Butene, 2-methyl-	000563-46-2	0,771
Air	1-Butene, 3-methyl-	000563-45-1	0,671
Air	1-Hexene	000592-41-6	0,874
Air	1-Pentene	000109-67-1	0,977
Air	1-Propanol	000071-23-8	0,561
Air	2-Butanol	000078-92-2	0,4
Air	2-Butanone, 3-methyl-	000563-80-4	0,364
Air	2-Butanone, 3,3-dimethyl-	000075-97-8	0,323
Air	2-Butene (cis)	000590-18-1	1,146
Air	2-Butene (trans)	000624-64-6	1,132
Air	2-Hexanone	000591-78-6	0,572
Air	2-Hexene (cis)	007688-21-3	1,069
Air	2-Hexene (trans)	004050-45-7	1,073
Air	2-Methyl-1-propanol	000078-83-1	0,36
Air	2-Methyl-2-butene	000513-35-9	0,842
Air	2-Methyl pentane	000107-83-5	0,42
Air	2-Pentanone	000107-87-9	0,548
Air	2-Pentene (cis)	000627-20-3	1,121
Air	2-Pentene (trans)	000646-04-8	1,117
Air	2-Propanol	000067-63-0	0,188
Air	3-Hexanone	000589-38-8	0,599
Air	3-Methyl-1-butanol	000123-51-3	0,433
Air	3-Pentanol	000584-02-1	0,595
Air	4-Methyl-2-pentanone	000108-10-1	0,49
Air	Acetaldehyde	000075-07-0	0,641
Air	Acetic acid	000064-19-7	0,097
Air	Acetic acid, methyl ester	000079-20-9	0,059
Air	Acetic acid, propyl ester	000109-60-4	0,282
Air	Acetone	000067-64-1	0,094

Air	Alcohol, diacetone	000123-42-2	0,307
Air	Benzaldehyde	000100-52-7	-0,092
Photochemical oxidation			
Category	Substance	CAS-number	[kg C₂H₄-eq/kg]
Air	Benzene, 1,2,3-trimethyl-	000526-73-8	1,267
Air	Benzene, 1,2,4-trimethyl-	000095-63-6	1,278
Air	Benzene, 1,3,5-trimethyl-	000108-67-8	1,381
Air	Benzene, 3,5-dimethylethyl-	000934-74-7	1,32
Air	Benzene, ethyl-	000100-41-4	0,73
Air	Butadiene	000106-99-0	0,851
Air	Butanal	000123-72-8	0,795
Air	Butane	000106-97-8	0,352
Air	Butane, 2,2-dimethyl-	000075-83-2	0,241
Air	Butane, 2,3-dimethyl-	000079-29-8	0,541
Air	Butanol, 2-methyl-1-	000137-32-6	0,489
Air	Butanol, 2-methyl-2-	000075-85-4	0,228
Air	Butanol, 3-methyl-2-	000598-75-4	0,406
Air	Butyl acetate	000123-86-4	0,269
Air	Chloroform	000067-66-3	0,023
Air	Cumene	000098-82-8	0,5
Air	Cyclohexane	000110-82-7	0,29
Air	Cyclohexanol	000108-93-0	0,518
Air	Cyclohexanone	000108-94-1	0,299
Air	Decane	000124-18-5	0,384
Air	Diethyl ether	000060-29-7	0,445
Air	Diethyl ketone	000096-22-0	0,414
Air	Diisopropyl ether	000108-20-3	0,398
Air	Dimethyl carbonate	000616-38-6	0,025
Air	Dimethyl ether	000115-10-6	0,189
Air	Dodecane	000112-40-3	0,357
Air	Ethane	000074-84-0	0,123
Air	Ethane, 1,1,1-trichloro-, HCFC-140	000071-55-6	0,009
Air	Ethanol	000064-17-5	0,399
Air	Ethanol, 2-butoxy-	000111-76-2	0,483
Air	Ethanol, 2-methoxy-	000109-86-4	0,307
Air	Ethene	000074-85-1	1
Air	Ethene, dichloro- (cis)	000156-59-2	0,447
Air	Ethene, dichloro- (trans)	000156-60-5	0,392
Air	Ethene, tetrachloro-	000127-18-4	0,029
Air	Ethene, trichloro-	000079-01-6	0,325
Air	Ethyl acetate	000141-78-6	0,209
Air	Ethylene glycol	000107-21-1	0,373
Air	Ethylene glycol monoethyl ether	000110-80-5	0,386
Air	Ethyne	000074-86-2	0,085
Air	Formaldehyde	000050-00-0	0,519
Air	Formic acid	000064-18-6	0,032
Air	Heptane	000142-82-5	0,494
Air	Hexane	000110-54-3	0,482
Air	Hexane, 2-methyl-	000591-76-4	0,411
Air	Hexane, 3-methyl-	000589-34-4	0,364
Air	Hydrocarbons, unspecified		0,337
Air	Isobutane	000075-28-5	0,307
Air	Isobutene	000115-11-7	0,627
Air	Isobutyraldehyde	000078-84-2	0,514
Air	Isopentane	000078-78-4	0,405
Air	Isoprene	000078-79-5	1,092
Air	Isopropyl acetate	000108-21-4	0,211
Air	m-Xylene	000108-38-3	1,108
Air	Methane	000074-82-8	0,006
Air	Methane, biogenic	000074-82-8	0,006

Air	Methane, dichloro-, HCC-30	000075-09-2	0,068
Air	Methane, dimethoxy-	000109-87-5	0,164
Photochemical oxidation			
Category	Substance	CAS-number	[kg C ₂ H ₄ -eq/kg]
Air	Methane, fossil	000074-82-8	0,006
Air	Methane, monochloro-, R-40	000074-87-3	0,005
Air	Methanol	000067-56-1	0,14
Air	Methyl ethyl ketone	000078-93-3	0,373
Air	Methyl formate	000107-31-3	0,027
Air	Nitric oxide	010102-43-9	-0,427
Air	Nitrogen dioxide	010102-44-0	0,028
Air	NMVOC, non-methane volatile organic compounds		1
Air	Nonane	000111-84-2	0,414
Air	o-Xylene	000095-47-6	1,053
Air	Octane	000111-65-9	0,453
Air	p-Xylene	000106-42-3	1,01
Air	Pentanal	000110-62-3	0,765
Air	Pentane	000109-66-0	0,395
Air	Pentane, 3-methyl-	000096-14-0	0,479
Air	Petrol	008006-61-9	0,42
Air	Propanal	000123-38-6	0,798
Air	Propane	000074-98-6	0,176
Air	Propane, 2,2-dimethyl-	000463-82-1	0,173
Air	Propene	000115-07-1	1,123
Air	Propionic acid	000079-09-4	0,15
Air	Propylene glycol	000057-55-6	0,457
Air	Propylene glycol methyl ether	000107-98-2	0,355
Air	Propylene glycol t-butyl ether	057018-52-7	0,463
Air	s-Butyl acetate	000105-46-4	0,275
Air	Styrene	000100-42-5	0,14
Air	Sulfur dioxide	007446-09-5	0,048
Air	Sulfur oxides		0,048
Air	t-Butyl acetate	000540-88-5	0,053
Air	t-Butyl alcohol	000075-65-0	0,106
Air	t-Butyl ethyl ether	000637-92-3	0,244
Air	t-Butyl methyl ether	001634-04-4	0,175
Air	Toluene	000108-88-3	0,637
Air	Toluene, 2-ethyl-	000611-14-3	0,898
Air	Toluene, 3-ethyl-	000620-14-4	1,019
Air	Toluene, 3,5-diethyl-	002050-24-0	1,295
Air	Toluene, 4-ethyl-	000622-96-8	0,906
Air	Undecane	001120-21-4	0,384

TABLE A34: CHARACTERIZATION FACTORS FOR EMISSIONS CONTRIBUTING TO ACIDIFICATION

Acidification			
Category	Substance	CAS-number	[kg SO ₂ -eq/kg]
Air	Ammonia	007664-41-7	1,6
Air	Nitrogen dioxide	010102-44-0	0,5
Air	Nitrogen oxides	011104-93-1	0,5
Air	Sulfur dioxide	007446-09-5	1
Air	Sulfur oxides		1

TABLE A35: CHARACTERIZATION FACTORS FOR EMISSIONS CONTRIBUTING TO EUTROPHICATION

Eutrophication			
Category	Substance	CAS-number	[kg PO ₄ -eq / kg]
Air	Ammonia	007664-41-7	0,35
Water	Ammonia	007664-41-7	0,35
Soil	Ammonia	007664-41-7	0,35
Air	Ammonium carbonate	000506-87-6	0,12
Air	Ammonium nitrate	006484-52-2	0,074
Soil	Ammonium nitrate	006484-52-2	0,074
Air	Ammonium, ion	014798-03-9	0,33
Water	Ammonium, ion	014798-03-9	0,33
Soil	Ammonium, ion	014798-03-9	0,33
Water	COD, Chemical Oxygen Demand		0,022
Air	Dinitrogen monoxide	010024-97-2	0,13
Water	Dinitrogen monoxide	010024-97-2	0,13
Soil	Dinitrogen monoxide	010024-97-2	0,13
Air	Nitrate	014797-55-8	0,1
Water	Nitrate	014797-55-8	0,1
Soil	Nitrate	014797-55-8	0,1
Air	Nitric acid	007697-37-2	0,1
Water	Nitric acid	007697-37-2	0,1
Soil	Nitric acid	007697-37-2	0,1
Air	Nitric oxide	010102-43-9	0,2
Water	Nitrite	014797-65-0	0,1
Water	Nitrogen	007727-37-9	0,42
Air	Nitrogen dioxide	010102-44-0	0,13
Air	Nitrogen oxides	011104-93-1	0,13
Water	Nitrogen oxides	011104-93-1	0,13
Soil	Nitrogen oxides	011104-93-1	0,13
Air	Nitrogen, total		0,42
Water	Nitrogen, total		0,42
Soil	Nitrogen, total		0,42
Air	Phosphate	014265-44-2	1
Water	Phosphate	014265-44-2	1
Soil	Phosphate	014265-44-2	1
Air	Phosphoric acid	007664-38-2	0,97
Water	Phosphoric acid	007664-38-2	0,97
Soil	Phosphoric acid	007664-38-2	0,97
Air	Phosphorus	007723-14-0	3,06
Water	Phosphorus	007723-14-0	3,06
Soil	Phosphorus	007723-14-0	3,06
Air	Phosphorus pentoxide	001314-56-3	1,34
Water	Phosphorus pentoxide	001314-56-3	1,34
Soil	Phosphorus pentoxide	001314-56-3	1,34
Air	Phosphorus, total		3,06
Water	Phosphorus, total		3,06
Soil	Phosphorus, total		3,06

TABLE A36: GROSS CALORIFIC VALUES OF NON-RENEWABLE ENERGY RESOURCES

Non-renewable energy			
Substance	CAS-number	Gross Calorific Value	Unit
Coal, 18 MJ per kg, in ground		25,3	MJ eq / kg
Coal, 26.4 MJ per kg, in ground		30	MJ eq / kg
Coal, 29.3 MJ per kg, in ground		30	MJ eq / kg
Coal, brown (lignite)		20	MJ eq / kg
Coal, brown, 10 MJ per kg, in ground		25,3	MJ eq / kg
Coal, brown, 8 MJ per kg, in ground		25,3	MJ eq / kg
Coal, brown, in ground		25,3	MJ eq / kg
Coal, feedstock, 26.4 MJ per kg, in ground		25,3	MJ eq / kg
Coal, hard, unspecified, in ground		30	MJ eq / kg
Gas, mine, off-gas, process, coal mining/kg	008006-14-2	43,1	MJ eq / kg
Gas, mine, off-gas, process, coal mining/m3	008006-14-2	39	MJ eq / m3
Gas, natural (0,8 kg/m3)	008006-14-2	30	MJ eq / m3
Gas, natural, 30.3 MJ per kg, in ground	008006-14-2	43,1	MJ eq / kg
Gas, natural, 35 MJ per m3, in ground	008006-14-2	39	MJ eq / m3
Gas, natural, 36.6 MJ per m3, in ground	008006-14-2	39	MJ eq / m3
Gas, natural, 46.8 MJ per kg, in ground	008006-14-2	43,1	MJ eq / kg
Gas, natural, feedstock, 35 MJ per m3, in ground	008006-14-2	39	MJ eq / m3
Gas, natural, feedstock, 46.8 MJ per kg, in ground	008006-14-2	43,1	MJ eq / kg
Gas, natural, in ground	008006-14-2	39	MJ eq / m3
Gas, off-gas, oil production, in ground	008006-14-2	39	MJ eq / m3
Gas, petroleum, 35 MJ per m3, in ground		39	MJ eq / m3
Methane	000074-82-8	55,52	MJ eq / kg
Oil, crude, 38400 MJ per m3, in ground		42158	MJ eq / m3
Oil, crude, 41 MJ per kg, in ground		43,76	MJ eq / kg
Oil, crude, 42 MJ per kg, in ground		43,76	MJ eq / kg
Oil, crude, 42.6 MJ per kg, in ground		43,76	MJ eq / kg
Oil, crude, 42.7 MJ per kg, in ground		43,76	MJ eq / kg
Oil, crude, feedstock, 41 MJ per kg, in ground		43,76	MJ eq / kg
Oil, crude, feedstock, 42 MJ per kg, in ground		43,76	MJ eq / kg
Oil, crude, in ground		43,76	MJ eq / kg
Uranium, in ground	007440-61-1	451000	MJ eq / kg

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